unesco

i-WSSM

International Centre for
Water Security and
Sustainable Management
under the auspices of UNESCO

The Role of Sound Groundwater Resources Management and Governance to Achieve Water Security

3

GLOBAL WATER SECURITY ISSUES SERIES

The Role of Sound Groundwater Resources Management and Governance to Achieve Water Security

Published by the United Nations Educational, Scientific and Cultural Organization (UNESCO), 7, place de Fontenoy, 75352 Paris 07 SP, France, and UNESCO International Centre for Water Security and Sustainable Management (i-WSSM), 125, Yuseong-daero 1689 beon-gil, Yuseong-gu, Daejeon, Republic of Korea

ISBN UNESCO 978-92-3-100468-1

Suggested citation: UNESCO and UNESCO i-WSSM. 2021. The Role of Sound Groundwater Resources Management and Governance to Achieve Water Security (Series III). Global Water Security Issues (GWSI) Series – No.3, UNESCO Publishing, Paris.

Editors

Seo Hyung Choi, UNESCO i-WSSM, Republic of Korea.
Eunher Shin, UNESCO i-WSSM, Republic of Korea.
Alexandros K. Makarigakis, UNESCO, France.
Okjoo Sohn, UNESCO, France.
Callum Clench, International Water Resources Association (IWRA), Portugal.
Mary Trudeau, Envirings Inc. and International Water Resources Association (IWRA), Canada.

Peer Reviewers

Hassan Tolba Aboelnga, Middle East Water Forum, Jordan.
Emmanuel Akpabio, University of Uyo, Nigeria.
Amali A. Amali, TH-Köln, University of Applied Sciences, Germany.
Ximing Cai, University of Illinois, United States.
Amgad Elmahdi, International Water Management Institute-MENA, Egypt.
Alfonso Expósito Garcia, University of Malaga, Spain.
Jan Hofman, Water Innovation and Research Centre, University of Bath, United Kingdom.
Muhammad Wajid Ijaz, Government of the Punjab-Lahore, Pakistan.
Wendy Jepson, Texas A&M University, United States.
William R. Jones, U.S. Food and Drug Administration Center for Food Safety and Applied Nutrition, United States.
Kanokphan Jongjarb, United Nations University and the University of Bonn, Germany.
Renée Martin-Nagle, A Ripple Effect pllc, United States.
Amrisha Pandey, Amity University, India.
Raya Marina Stephan, International Water Resources Association, France.
Maya Velis, World Bank, United States.

Authors

Enrique Fernández-Escalante, IAH MAR Commission / Tragsa, Spain.
Elena López Gunn, iCatalist Consulting, Spain.
Elisa Blanco, Pontificia Universidad Católica de Chile, Chile.
Guillermo Donoso, Pontificia Universidad Católica de Chile, Chile.
Amy Hardberger, Texas Tech University, United States.
Bruce Aylward, Mercy Corps, United States.
Victor R. Shinde, National Institute of Urban Affairs, India
Lovlesh Sharma, National Institute of Urban Affairs, India.
Yuanyuan Li, General Institute of Water Resources and Hydropower Planning and Design (GIWP), China.
Lili Yu, GIWP, China.
Yan Yang, GIWP, China.
Fengyue Sun, GIWP, China.
Yueyuan Ding, GIWP, China.
Jie Hou, GIWP, China.
Fei Chen, GIWP, China.
Shinan Tang, GIWP, China.
David Adamson, University of Adelaide, Australia.
Christopher Auricht, University of Adelaide and Auricht Projects, Australia.
Adam Loch, University of Adelaide, Australia.
Simon G. Craig, IHE Delft – Institute of Water Education, The Netherlands.
Chen Lester R. Wu, IHE Delft – Institute for Water Education, The Netherlands.
Tibor Y. Stigter, IHE Delft – Institute for Water Education, The Netherlands.
Jacobs Groen, Groen Water Solutions, The Netherlands.
Malcolm J. Gander, Department of Defense, United States.
Frida Cital, Universidad Autónoma del Estado de Baja California, Mexico.
Alfonso Rivera, Geological Survey of Canada, Canada.
Eliana Rodríguez-Burgueño, Universidad Autónoma del Estado de Baja California, Mexico.
Jorge Ramírez-Hernández, Universidad Autónoma del Estado de Baja California, Mexico.
Julie Trottier, Centre National de la Recherche Scientifique, France.
David B. Brooks, International Institute for Sustainable Development, Canada.
Maureen Walschot, Université catholique de Louvain and the University of Haifa, Belgium.
Wagner Costa Ribeiro, Universidade de Sao Paulo, Conselho Nacional de Desenvolvimento Científico e Tecnológico, Brazil.
Piet K. Kenabatho, University of Botswana, Botswana.
Thato S. Setloboko, Department of Water and Sanitation, Botswana.
Bertram Swartz, Department of Water Affairs and Forestry, Namibia.
Maria Amakali, Department of Water Affairs and Forestry, Namibia.
Kwazikwakhe Majola, Department of Water and Sanitation, South Africa.
Ramogale Sekwele, Department of Water and Sanitation, South Africa.
Rapule Pule, Orange-Senqu River Commission (ORASECOM), South Africa.
Michael Ramaano, Orange-Senqu River Commission (ORASECOM), South Africa.
Koen Virbist, UNESCO Regional Office for Southern Africa (ROSA), Zimbabwe.
Alice Aureli, UNESCO-IHP, France.
Tarisai Kanyepi, Pan African University of Water, Energy Sciences & Climate Change, Algeria.
Vincent Itai Tanyanyiwa, Zimbabwe Open University, Zimbabwe.
Liberty Moyo, Namibia University of Science and Technology, Namibia.

Acknowledgement

We acknowledge with gratitude the support provided by the International Water Resources Association (IWRA).

Cover and inside design: ©Junghwan Kim, Pieona Books & UNESCO i-WSSM
Cover photo (front): ©LALS STOCK/Shutterstock. Portugal
Cover photo (back): ©thieury/Shutterstock. France

Printed in Seoul, Republic of Korea by Pieona Books

SHORT SUMMARY

Groundwater, invisible to visible

The true value of groundwater is hidden beneath the ground. Often, general public and policy-makers are not fully aware of the importance of this precious resource, even though **groundwater provides nearly 50% of all drinking water**. While the pressure on groundwater has been steadily increasing, this invisible resource continues to receive less attention than it deserves.

This Global Water Security Issues (GWSI) Series 3, The role of sound groundwater resources management and governance to achive water security explores various case studies of tools and analyses of management, groundwater quality issues, transboundary aquifer management, and stakeholder engagement. The GWSI shines a spotlight on groundwater resources to highlight the importance of integrated water resource management and strengthened capacity for robust management decisions.

- The increasing depletion and contamination of groundwater resources are putting water security at risk
- Water security is achieved when groundwater governance ensures an interaction across all social groups

Groundwater provides nearly **50%** **of all drinking water.**

The current phase of the UNESCO-IHP focuses on thematic areas that include groundwater in a changing environment. This Global Water Security Issues by UNESCO and UNESCO i-WSSM is one implementation for achieving the SDGs.

unesco

"Since wars begin in the minds of men and women it is in the minds of men and women that the defences of peace must be constructed"

The Role of Sound Groundwater Resources Management and Governance to Achieve Water Security

3

GLOBAL WATER SECURITY ISSUES SERIES

i-WSSM

International Centre for
Water Security and
Sustainable Management
under the auspices of UNESCO

Foreword

Abou Amani
Director, UNESCO Division of Water Sciences a.i.

Groundwater is a fundamental part of the hydrological cycle and the environment at large, for its crucial role in sustaining ecosystems, maintaining the baseflow of rivers, as well as preventing land subsidence and seawater intrusion. This precious resource is equally important for human activities, serving as a source of drinking water, irrigation, and even industrial water. Despite these invaluable dimensions, groundwater is often undervalued because it is largely invisible to the naked eye.

Recently, groundwater is being placed under increasing pressure globally as a result of human activities and climate change. Rapid population growth, changes in consumption patterns, increasing demand of water, rapid urbanization, and climate change are all factors that are threatening groundwater security. Although groundwater is a renewable resource, its recharge requires a long time. Increased withdrawals from groundwater systems can lower the water table, which can shrink rivers and wetlands, create saltwater intrusion in freshwater areas, as well as land subsidence. Groundwater contamination issues, including point source and non-point source, are also becoming more common by the day. Transboundary groundwater can even lead to social unrest and spark conflict within and between countries.

In response to this escalating risk, groundwater security is becoming an urgent need, particularly in light of the approaching deadline of the 2030 Agenda for Sustainable Development. Access to safe and affordable drinking water, improved groundwater quality, and groundwater recharge are all essential for the achievement of the Sustainable Development Goal 6 dedicated to water. Moreover, groundwater also serves as an essential foundation for the achievement of several other SDGs, by contributing to reduce poverty (SDG 1) and hunger (SDG 2), ensuring health and well-being (SDG 3), promoting gender equality (SDG 5), sustaining cities and human settlements (SDG 11), supporting climate change adaptation (SDG 13), and sustaining ecosystems (SDG 15).

With this understanding, this year's Global Water Security Issues Series 3 outlines the important role of groundwater in the context of water security, which UNESCO-IHP (Intergovernmental Hydrological Programme) highlights. I would like to express my gratitude to the International Centre for Water Security and Sustainable Management (i-WSSM), the International

Water Resources Association (IWRA), and all authors, editors and staff involved in publishing this series. I sincerely hope that this publication will shed light on the imminent and critical groundwater issues we are facing today, in order to make the invisible visible, and pave the way to achieving global water security.

Abou Amani
Director, UNESCO Division of Water Sciences a.i.

Foreword

Bong-woo Shin
Director of UNESCO i-WSSM

Beneath the ground we stand on, a vast amount of water exists beyond our sight. Groundwater is one of the most valuable resources of our day, serving our daily water needs for a wide range of agricultural, industrial, municipal, and domestic purposes.

The role that groundwater plays in the hydrological cycle is essential. Precipitation infiltrates to the ground and flows into rivers, streams, lakes, ponds, oceans, or deeper into the ground. In water circulation, groundwater discharge can contribute significantly to the environment. Conversely, contaminated groundwater sources can change soil properties, adversely affecting ecosystems. For this reason, securing adequate quantities and qualities of groundwater is crucial for achieving global water security.

Groundwater is, however, under increasing pressure. Overexploitation, climate change, increase in water demand due to population growth, and urbanization are all putting a strain on groundwater usage. Overexploitation of groundwater lowers the water table, which can lead to saltwater intrusion and land subsidence. Toxic materials and chemicals in groundwater can also cause serious impacts on not only human health but also the environment. Political, institutional, and socioeconomic factors are also threatening transboundary groundwaters worldwide, through increased conflicts between and within countries. Despite all of these imminent risks, the awareness and concerns about this vital resource are not sufficient.

The current eighth phase of UNESCO's Intergovernmental Hydrological Programme (IHP) focuses on water security, which is also key for achieving the 2030 Agenda for Sustainable Development. The role that groundwater plays in both water security and the 2030 Agenda, therefore, cannot afford to be overlooked. Groundwater plays a pivotal role towards not only the Sustainable Development Goal (SDG) 6, "Ensure access to water and sanitation for all," but also for numerous other SDGs.

As a result, this year's Global Water Security Issues Series 3 contributes to this important issue by providing several case studies related to stakeholder engagement, groundwater management and analysis, groundwater quality, and transboundary aquifer management. I wish to express my sincere gratitude to UNESCO, the International Water Resources Association (IWRA),

as well as all authors and editors for bringing this important publication to life.
I sincerely hope that this publication will help contribute to raising awareness and attention towards the true value and significance of the essential resource that is groundwater.

Bong-woo Shin
Director of UNESCO International Centre for Water Security and Sustainable Management

Contents

Part I

Stakeholder Engagement

3

Part II

Tools for Management

II. TOOLS FOR MANAGEMENT

Part III

Tools for Analysis

III. TOOLS FOR ANALYSIS

6

7

Part IV

Remediation

IV. REMEDIATION

8

Part V

Transboundary Aquifer Management

V. TRANSBOUNDARY AQUIFER MANAGEMENT

Part V

Transboundary Aquifer Management

13

Figures

Tables

Abbreviations & Acronyms

AWS	Africa Water Commission
BDP	Bhopal Development Plan
BMCs	Basin Management Committees
BWRC	Basin Water Resource Committees
CBM	Community Based Management
CDL	Current Diversion Limit
CEA	State Water Commission
CESPM	State Commission of Public Services of Mexicali
CLU	Change in Land Use
CONAGUA	National Water Commission
COTAS	Technical Groundwater Council
CPIA	Country Policy and Institutional Assessment
CUA	Groundwater Users Association
DDF	District Development Fund
DGA	Dirección General de Aguas
DO	Dissolved Oxygen
DSS	Decision Support Systems
DWA	Department of Water Affairs
DWRD	Department of Water Resources and Development
EC	Electrical Conductivity
EIA	Environmental Impacts Assessment
FAES	Flame Atomic Emission Spectroscopy
FAO	Food and Agriculture Organization
FAR	Floor Area Ratio
FTL	Full Tank Level
FWL	Freshwater Lens
GAB	Great Artesian Basin
GDP	Gross Domestic Product
GGRETA	Groundwater Resources in Transboundary Aquifers
GIS	Geographic Information System
GMI	Groundwater Management Institute
GUI	Graphical User Interface
GWHC	Groundwater Hydrology Committee
GWP	Global Water Partnership
HDI	Human Development Index
IAD	Institutional Analysis and Development
IBWC	International Boundary and Water Commission
ICS	Ion Chromatography System
IGRAC	International Groundwater Resources Assessment Centre
IHP	UNESCO Intergovernmental Hydrological Programme
IMTA	Mexican Institute of Water Technology
INGO	International Non-Governmental Organization
IWRM	Integrated Water Resources Management
JPTC	Permanent Joint Technical Commission
JPWC	Joint Permanent Water Commission
JVA	Jordan Valley Authority
KGMP	Kenya Groundwater Mapping Programme
LAN	National Water Law
LCRB	Lower Colorado River Basin Transboundary Aquifer
LGC	LIMCOM Groundwater Committee
LHWP	Lesotho Highlands Water Project
MAC	Maximum Allowable Concentration
MAR	Managed Aquifer Recharge
MAWF	Ministry of Agriculture, Water & Forestry
MCCM	Multi-Country Cooperation Mechanism
MDB	Murray-Darling Basin
MENA	Middle East and North Africa
MTCID	Ministry of Transport, Communication and Infrastructural Development
MVA	Mexicali Valley Aquifer
MWDSEP	Ministry of Development, Sanitation and Environmental Protection
NamWater	Namibia Water Corporation
NAS	Nairobi Aquifer System
NDC	National Development Corporation
NGO	Non-Government Organization
NMDB	Northern Sustainable Diversion Limit
NSW	New South Wales
NWASCO	National Water Supply and Sanitation Council
OKACOM	Permanent Okavango River Basin Water Commission
ORASECOM	Orange River and Sengu Commission
PMU	Performance Monitoring Unit
PPP	Public-Private Partnership
PPPP	Public-Private People Partnership
PWC	Permanent Water Commission
RBOs	River Basin Organizations
REPDA	Public Registry of Water Rights
RWD	Relative Water Demand
SA	South Australia
SADC	Southern African Development Community
SAP	Strategic Action Plan
SCA	State-Contingent Approach

SDC	Swiss Agency for Development and Cooperation
SDGs	Sustainable Development Goals
SDL	Sustainable Diversion Limit
SDRL	Limited Responsibility Society
SEMARNAT	Department of Environment and Natural Resources
SEPROA	Secretary for the Management, Sanitation and Protection of Water
SES	Social-Ecological Systems
SGMA	Sustainable Groundwater Management Act
SI	Saturation Index
SIS	Salinity Interception Schemes
SLRC	San Luis Rio Colorado
SMDB	Southern Sustainable Diversion Limit
SSA	Sub-Saharan Africa
STAS	Stampriet Transboundary Aquifer System
SWOT	Strength-Weakness-Opportunity-Threats
TBA	Transboundary Aquifer
TDA	Transboundary Diagnostic Analysis
TDLAS	Tunable Diode Laser Absorption Spectroscopy
TDR	Transferable Development Rights
TDS	Total Dissolved Solids
TI-CPI	Transparency International's Corruption Perceptions Index
TORs	Terms of Reference
TTT	Technical Task Team
TWINS	Transboundary Water Interactions Nexus
UN	United Nations
UN DESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNDRR	United Nations Office for Disaster Risk Reduction
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations International Children's Emergency Fund
USGS	United States Geological Survey
UZF	Unsaturated Zone Flow
VES	Vertical Electrical Soundings
VIC	Victoria
VSMOW	Vienna Standard Mean Ocean Water
WAJ	Water Authority of Jordan
WARFSA	Water Research Fund for Southern Africa
WARMA	Water Resources Management Authority
WASH	Water, Sanitation and Hygiene
WASP	Water and Sanitation Sector Policy
WEI	Water Exploitation Index
WHO	World Health Organization
WMO	World Meteorological Organization
WPCs	Water Point Committees
WRA	Water Resources Authority
WRMA	Water Resources Management Authority
WRUA	Water Resources Users Association
WSS	Water Supply and Sanitation
WSUD	Water Sensitive Urban Design
WUAs	Water Users' Associations
WWAP	UNESCO World Water Assessment Program
WWTP	Wastewater Treatment Plant
ZINWA	Zimbabwe National Water Authority

Introduction

The theme for this third publication of the UNESCO i-WSSM Global Water Security Issues is the role of sound groundwater resources management and governance to achieve water security. As an underground resource, often called the invisible resource, groundwater is more difficult to quantify, assess and monitor than surface water resources. In addition, the general public and many decision-makers are often not aware of the need for careful management of groundwater resources, or the best practices to steward these resources for current and future generations. When groundwater is withdrawn faster than an aquifer can recharge, many problems can arise, such as ground subsidence and water quality deterioration. Also, when water withdrawal exceeds water recharge, aquifers are no longer sustainable resources. Further, some aquifers were formed many thousands, or even millions, of years ago and the climatic conditions that created them no longer exist, so these aquifers do not refill when water is withdrawn. Water withdrawn from aquifers that do not recharge results in the depletion of a non-renewable resource. Gaps in mapping and quantification of aquifer resources compound the multiple challenges of managing an underground resource. Climate change will affect, and is already affecting, natural conditions that influence groundwater, such as soil moisture, evaporation rates, spatial and temporal precipitation patterns, recharge rates, and chemical processes (such as oxidation and reduction reactions) that influence water quality, water quantity and seasonal water availability.

Groundwater interacts with surface water, and all water systems operate within geophysical spaces that are not delineated by political borders. Groundwater recharge zones may be located in a geopolitical region that is different from the location of groundwater use. Further, two or more countries may draw water from the same aquifer, creating a need for transboundary cooperation. These management challenges must be met while also navigating intra- and international jurisdictional authorities. There are numerous transboundary aquifers globally that can be found beneath virtually all land-based jurisdictional borders in non-island nations, requiring collaborative and cooperative management approaches. Even within contested areas, groundwater offers an opportunity to move towards peace and collaboration over shared objectives. Chapters in this publication provide case studies, literature reviews, tools, and protocols for groundwater resources management and governance, with the aim to achieve water security.

Sound groundwater resources management is essential to achieve the

Sustainable Development Goals (SDGs), in particular SDG 6, Ensure availability and sustainable management of water and sanitation for all, SDG 11, Make cities and human settlements inclusive, safe, resilient and sustainable, and SDG 12, Ensure sustainable consumption and production patterns. UNESCO Intergovernmental Hydrological Programme (IHP) recognizes water security is a key challenge for the 21st century during its 8th phase, IHP-VIII and maintains water security as a priority in the upcoming 9th Phase, IHP-IX. The IHP works to build a scientific knowledge base for water resources management and governance, and facilitates education and capacity building. To develop tools to adapt to changing water availability, the IHP engages in, and supports, hydrological and socioeconomic research. The current phase of the IHP focuses on thematic areas that include: the water cycle and water related hazards; groundwater in a changing environment; addressing water scarcity and quality; water and human settlements of the future; and, water education as a water security strategy. This UNESCO i-WSSM Global Water Security Issues is one initiative to translate science into action for a sustainable future.

Stakeholder engagement is a theme that runs through many of the chapters of this edition of the Global Water Security Issues. Case studies in Spain and Chile exemplify the benefits of modifying the “top-down” approach to groundwater management by engaging stakeholders at a grassroots level. In the region of Castilla Leon in the Spanish part of the Douro (Duero) river basin (Chapter 1, Fernández-Escalante and Gunn), a “space for collaboration” was nurtured to build trust among groundwater user groups, including farmers, and water authorities. With a recognized and legitimate role in decision-making, the groundwater users’ communities provided input to decisions on water use, water quality standards, and the operation of infrastructure for managed aquifer recharge (MAR).
The outcome is a robust integrated water resources management (IWRM) approach for the source of water for up to 25% of the agricultural irrigation in the region. Management of Chile’s Copiapó basin (Chapter 2, Blanco and Donoso) also benefited from the creation of a forum where all stakeholders could provide input in a neutral space. The discussions were facilitated by a team of mediators with technical expertise. Collective action was gradually enabled through stakeholder discussions, and the process has overcome impediments such as a lack of monitoring information, serious trust issues, and disconnection between surface and groundwater administration. As part of a consistent and transparent process to improve groundwater management, legal language and stakeholder representation were established, consensus on a registry of water rights was obtained, and innovative strategies were explored. Leaders from the stakeholder groups were identified and empowered in conjunction with limiting administrative authority in the community’s decisions. There remains work to be done but the

tools applied in these case studies are more broadly applicable.

In arid and semi-arid countries, for example in the Middle East/ North Africa (MENA) and Sub-Saharan Africa, there is a high reliance on groundwater resources for food and drinking water. The important role of local governments and civil society is amplified in states where ongoing conflict, cross-border refugees, displaced peoples, lack of financial resources and potential political corruption interfere with the capacity of national or regional governments to manage natural resources, including groundwater. In Jordan and Kenya (Chapter 3, Hardberger and Aylward), essential measures at the local level can enable successful governance in communities that are distant from cities and in formal government structures. Rather than focussing on what centralized authorities can do, communities, local governments and non-government organizations can collaborate to manage local resources. For instance, local capacity to manage groundwater resources can be built through proactive efforts to compile and share data on groundwater and tenure systems, in concert with activities to raise community awareness about the resource.

Domestic policies and approaches to groundwater management can be deployed in a variety of ways and two chapters provide insights to management tools, one at the municipal scale and one at a national scale. In India (Chapter 4, Shinde and Sharma), groundwater management tools and measures have been incorporated into city Master Plans to protect water resources. Examples from fifteen cities profile a range of instruments, including design elements, planning approaches, economic instruments, and others, that have been deployed to protect India's groundwater resources. For example, a floor area ratio (FAR) divides the total amount of usable floor area of a building by the area of the plot of land on which the building is situated. This ratio is used to assess the density of a proposed development or redevelopment with respect to available water resources. The FAR has been successfully applied in Delhi to alter growth plans in neighbourhoods drawing from stressed aquifers. This tool, and others, are transferable to other municipalities and to other aspects of urban sustainability beyond groundwater as well. In China (Chapter 5, Li *et al.*), a national classification system for groundwater resources is the central feature of a framework to manage and control groundwater exploitation. Four levels of management priorities include: maintaining a dynamic water cycle; considering the needs of both nature and humans; keeping a reserve supply for unexpected events; and, prioritizing use to match quality needs. Groundwater resources place a firm restraint on economic and social development. Through the application of this framework, groundwater consumption rates in China have stabilized with no recent growth.

Modelling tools are useful to understand the implications of potential scenarios and decision choices. Two chapters explore very different modelling tools, in context of other management techniques: one an economic model and the other a numerical groundwater model. In Australia's Murray-Darling Basin (Chapter 6, Adamson, Auricht, and Loch), an economic modelling analysis of groundwater as a more reliable source of water for agricultural use reveals the business decision shifts that would occur in agriculture in comparison with decisions based on access only to the highly variable surface flows of the basin. Using water availability under three climate change scenarios, from drought to flood conditions, farmers' response to risk and uncertainty were modelled, assuming the natural capital of the aquifer system is maintained and preserved. Spatial and hydrochemistry modelling of groundwater on Delft Island, Sri Lanka (Chapter 7, Craig *et al.*) simulates the interaction of fresh and saline waters with abstraction practices on the small coral-limestone island. Numerical modelling was complemented by field assessments, including well inventories, interviews with residents and other data collection activities, to develop potential options for managing the vulnerable freshwater resource and protecting its water quality.

Water quality is an overarching concern for groundwater, and climate change potentially brings additional stressors to quality (Chapter 8, Gander). Both anthropogenic and naturally-occurring pollutants should be considered when determining potential groundwater quality remediation techniques. Managing uses to appropriately match available water quality is an approach that can optimize remediation investments. For instance, industrial and some agricultural uses may be suited to application of lower water quality. Climate change is altering the concentration, dilution, and transport of pollutants in a variety of ways but understanding pollutants, remediation options, and the potential influences of climatic trends are important considerations for policy makers in making funding and resource allocation decisions.

Transboundary resources require additional efforts, beyond single state actions, to develop and foster binational, or multinational, management agreements and processes. SDG 6.5.2 monitors cooperation on transboundary aquifers by assessing the percentage of transboundary basin area within a country that has an operational water cooperation arrangement. Criteria for arrangements that are operational are also established through the SDG. Five chapters profile transboundary aquifer management. The Lower Colorado River Basin Aquifer is a transboundary aquifer underlying parts of the states of California and Arizona in the United States, and the regions of Baja California and Sonora in Mexico (Chapter 9, Cital *et al.*). There is little mention of sharing aquifer waters in treaties between the United States and Mexico. Management difficulties arising from insufficient monitoring of water quality and quantity, and poor management practices by some users in the agricultural sector, which is the largest user of water in the shared aquifer, compound the lack of financial and staff capacity of the Mexican government to ensure compliance with regulatory requirements. Collaboration with academic centers, creation of a Technical Groundwater Council, and guidance from government agencies have alleviated some of the challenges but an integrated plan with indicators and metrics is needed for the aquifer. Understanding water as a flow, rather than a resource stock, is proposed as an approach to more fully assess water security and the linkages among actors who deploy governance strategies over multiple scales (Chapter 10, Trottier and Brooks). A case study of the West Bank in Palestine profiles this approach, examining the interaction between wells and springs, wastewater reuse, and irrigation in the Jordan Valley in an approach that includes the activities of actors that would otherwise not be visible through a water stock analysis.

Seven countries in Central America share 23 international watercourses and 18 transboundary aquifers, offering an opportunity to assess the status transboundary aquifer cooperation through evaluation of eight enabling factors (Chapter 11, Walschot and Ribeiro). After gauging the level of engagement among states to be high, moderate or low with respect to transboundary aquifer collaboration, key missing factors are identified in this case study. In this region, even where international agreements are in place, there remains a need to develop legal mechanisms, to further engage local stakeholders, and to bring strong political will to build capacity for managing the unseen resources in aquifers. In Central America, and elsewhere, water security can create a path to peace and away from conflict.

In Southern Africa, the Stampriet Transboundary Aquifer System is a crucial water resource shared by Namibia, Botswana and South Africa (Chapter 12, Kenabatho *et al.*). Work initiated in 2013 by the three countries, in collaboration with UNESCO's Intergovernmental Hydrological Programme and the Swiss Agency for Development and Cooperation, has culminated in the establishment of a groundwater governance mechanism that is nested within a previously established institution, the Orange-Senqu River basin Commission. This arrangement ensures the knowledge and collaboration achieved through the initial project can transcend the project. Further, the experience gained can be transferred to other transboundary aquifers to establish governance mechanisms elsewhere in the region. The urgency to establish effective groundwater governance mechanisms in Southern Africa, and the basis for transboundary agreements, is discussed through a review of existing water policies of Zimbabwe, Namibia and Zambia (Chapter 13, Kanyepi *et al.*). The recurring themes of strengthening political will and building the capacity of stakeholders to actively participate in groundwater management are also highlighted in this chapter.

Groundwater is an unseen resource that often receives less attention than surface water resources, even though it plays an essential role in water security for millions of people worldwide. It also supplies baseflows to rivers and other surface water systems, supporting aquatic ecosystem stability and health. This edition of the Global Water Security Issues shines a spotlight on this precious resource to highlight the importance of integrated water resource management and strengthened capacity for robust management decisions.

I

Stakeholder Engagement

©CHOTE BKK/Shutterstock.

1

Co-managed Aquifer Recharge: Case Studies from Castilla y León (Spain)

Enrique Fernández-Escalante and Elena López Gunn

Enrique Fernández-Escalante, IAH MAR Commission / Tragsa, Spain.
e-mail: 4marer68@gmail.com
Elena López Gunn, iCatalist Consulting, Spain.
e-mail: elopezgunn@icatalist.eu

Abstract

Spanish regulation requires that, for every intensely exploited aquifer, the responsible water authorities must coordinate actions with an appointed groundwater users' community (CUAS), as a unique and legitimate counterpart to negotiate and reach agreements. This modifies the traditional "top-down" approach as a space for collaboration, in which groundwater users can collaborative with each other and members of the general public have the possibility to provide inputs into decision making, seeking collective benefits, like for example, controlling water use practices and, specifically, improving and securing future water supply and water quality standards for long term agricultural development.

Shared data, information, and knowledge by all stakeholders, in particular the river basin agency, the CUAS (including farmers) and the population in general help to design more robust decision support systems (DSS) and thus the identification of adequate agreed management response measures to address intensive groundwater use.

A "space for collaboration" is created based on trust on the fair use of (ground)water resources, with strong functional organizational structures that help take decisions with direct positive outcomes on improved groundwater quality and quantity. This space becomes the basis for new governance arrangements that are better suited and more responsive to the collective interest of all users.

The paper demonstrates through real case studies in the region of Castilla y León in the Spanish part of the Duero river basin how Public-Private People Partnership (PPPP), through groundwater users associations and their relation with authorities and among users, enhance governance for better regional water security. In particularly how the combination of hard structural measures like managed aquifer recharge, when combined with soft nonstructural measures, like the creation of groundwater user groups, creates the right "space for collaboration" for co-management of conjunctive use of water resources. Looking at the case of groundwater bodies and their respective groundwater user communities in El Carracillo, Medina del Campo, Cubeta de Santiuste de San Juan Bautista and Alcazarén, and the experiences and socio-technical changes from the introduction of Managed Aquifer Recharge (MAR) facilities that provide between 22 and 25% of the total amount of water used for irrigation in the area.

For this paper we have used a mixed methods approach consisting of a literature review and case study analyses which combines primary data, with more than 50 interviews and a series of workshops over time. Both MAR and CUAS will serve as entry points to understand the full system, including other integrated water resources management (IWRM) measures.

Keywords

Regulations, governance, water security, co-management, Groundwater Users Association (CUA), Managed Aquifer Recharge, MAR, Co-Managed Aquifer Recharge, Co-MAR, space for collaboration, stakeholders, stakehomers, drought management, over-exploitation, Public-Private Partnership (PPP), Public-Private People Partnerships (PPPP), Decision Support Systems (DSS)

01
Introduction

In many areas across the world, groundwater is experiencing a lot of pressure due to the intensive use of aquifers, which has often been closely related to agricultural development. When water management is not properly addressed, the risk of groundwater overexploitation is triggered, and is often linked to irrigation activities. In this context, innovative technological and management solutions are emerging to deal with intensive use of groundwater, and are likely to become even more complex under climate change. In practical terms, the different interests have to align to achieve sustainable growth within the operating space of available resources (MARSOL, 2016b; Mayor *et al.*, 2020).

> *"Groundwater is experiencing a lot of pressure due to the intensive use of aquifers, which has often been closely related to agricultural development"*

This paper looks at the case of Castilla y León (Spain) and a large hydrogeological system in inland Spain in the Duero river basin ("Duero" in Spanish or "Douro" in Portuguese) to document experiences in relation to what we have termed "co-managed aquifer recharge". In the case studies, there is strong collaboration with water user communities to address aquifer intensive use and overexploitation by incorporating Managed Aquifer Recharge (MAR) as a way to help re-balance the system to a sustainable resource extraction level.

According to FAO and UNESCO (2003), agricultural development aims to improve agricultural people's livelihoods, both socially and environmentally, through better access to assets (natural, physical, human, technological, and social capital), services, and better control over productive capital (in its financial, economic and political forms).

The paper analyses this space for collaboration in two different groundwater bodies (Los Arenales and Medina del Campo) within the autonomous region of Castilla León in Spain, considered to be in "poor status" under the EU Water Framework Directive. These are co-managed by four irrigation communities in El Carracillo, Medina del Campo, Santiuste de San Juan Bautista and Alcazarén. One of the common issues among all the stakeholders is the use of alternative water management techniques; in particular MAR has been introduced as a water management measure to address intensive aquifer use, and to reduce impacts on the aquifer from intense groundwater extraction for irrigation. Thus, these four groundwater user communities and two aquifers have relied on MAR to improve the potential for water availability and water security. These cases represent some of the biggest MAR systems in Spain. In some cases, the water user groups have even acted as promoters, proposing the creation of MAR facilities, while also helping to design co-management rules with the Duero river basin agency (Confederación Hidrográfica del Duero or CHD). Both MAR and co-management combined become elements to succeed in better coordination of aquifer management and planning to secure the long-term livelihoods in the area.

Most aquifers share common hydrogeological features, where the creation of a "space for collaboration" helps to explain how stakeholder involvement in groundwater management may translate into better management outcomes, more robust water governance and ultimately better water security. It is a bottom-up approach in which both users and the population are effectively engaged in the co-management of the resource, and - herein lies the innovative aspect- in the co-management of the introduced solutions in which all inhabitants take part.

The paper has been structured as follows. First, we introduce the problem, the issue of aquifer intensive use for agricultural development and the two main measures implemented: MAR and collective management, as an integrated solution. Second, we introduce the case study areas and their main characteristics in terms of hydrogeological resources, managed aquifer recharge initiatives and the creation of water user groups. Third, we analyse what we have called "co-management of aquifer recharge" experience by looking at some key elements to help create collaborative spaces among all stakeholders for better informed decision making that provide an opportunity for more efficient, equitable and sustainable groundwater use in the area. Finally, we conclude with some recommendations and areas of further work that could be of interest to other parts of the world facing similar challenges of intensive groundwater use for agricultural development regions.

02

Background information to this study

2.1. Intensive groundwater use cases in Castilla y León

Overexploitation may be defined as the situation in which, for some years, the average aquifer abstraction rate is greater than, or close to, the average recharge rate. However, the rate and extent of recharge areas are often very uncertain, together with the fact that these may be further modified by aquifer development itself and human activities.
In practice, an aquifer is often considered as overexploited when some constant negative impacts are identified, such as a continuous water-level drawdown, progressive water-quality deterioration, an increase of abstraction costs, or ecological damages. Negative impacts do not necessarily always imply that abstraction is greater than recharge.
It may simply be due to a case of well interferences and the transient period that follows changes in the aquifer water balance (Custodio, 2002). Also, groundwater sustainability is understood, as "*the development and use of groundwater in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic or social consequences*" (United States Geological Service, Circular 1,186, (2012)). Consequently, the term "*overexploitation*" has specific nuances, and, in this case, it is preferable to apply the term "*intensive exploitation of groundwater*".

In Spain, there are two ways that indicate whether an aquifer is intensively exploited or even legally overexploited.
First, there is the classification under the EU Water Framework directive for groundwater bodies and whether these are in good or poor status. Second, there is the classification based on the so-called Water Exploitation Index (WEI).
According to the Spanish Water Act, Art. 40, each aquifer with a WEI exceeding 0.80 requires intervention by the Water Authorities. The WEI is defined as the ratio of withdrawals to inputs in a system. When the WEI exceeds the value of 0.4-0.6, the system is subject to a very high-water stress. For example, due to the increase of irrigated agriculture groundwater abstractions in the water body 020.045, Los Arenales (Figure 1-1), the groundwater table registered a progressive decline of about 25 m between 1972 and 2002 (Figure 1-2 and Table 1-1). The same situation applies to the Medina del Campo water body, where the groundwater level declined by 30 m for the same period (Figure 1-3 and Table 1-1). According to the Duero River Basin Plan (PHD, 2016), the WEIs are 1.30 and 1.65 respectively. This intense exploitation has as a clear impact on environmental deterioration of the area

Between 1972 and 2002, a 25 m groundwater decline was registered for the whole aquifer; within the last 18 years there has been a small level of recovery thanks to MAR, which has reduced the decline to 15 m.

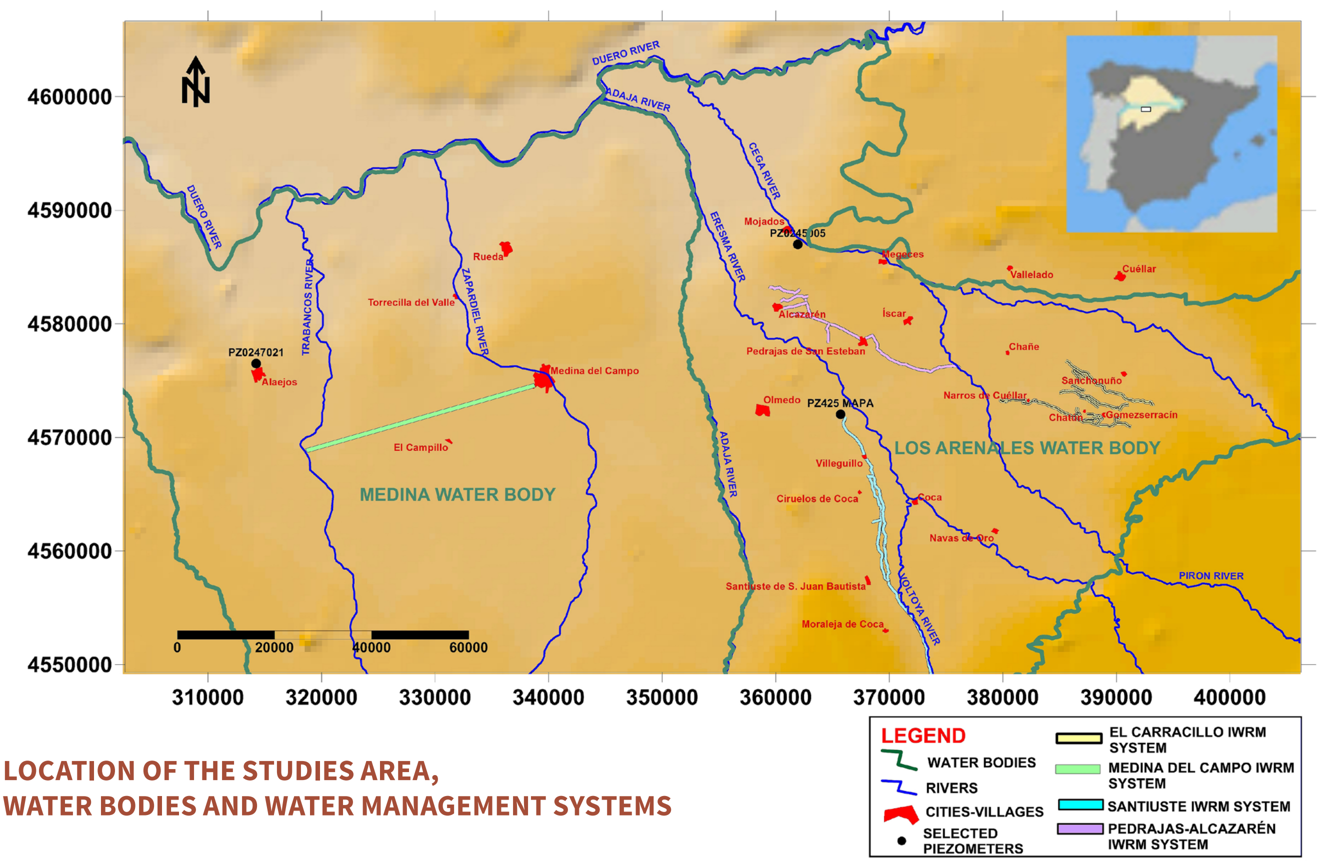


Figure 1-1 *Location of case study water bodies, IWRM infrastructure, MAR systems and related rivers, position of the selected piezometers and main villages*

Both Figure 1-2 and Figure 1-3 show a downward water table trend. In addition, both show a poor qualitative status from diffuse pollution, with nitrates concentrations nearing the Maximum Allowable Concentration (MAC) for some areas.

The quantitative status of the Los Arenales groundwater body DU-400045 and Medina del Campo groundwater body DU-400047 are "poor" (PHD, 2016, Annex 1). For Los Arenales case, the nitrates concentration exceeds 50 ppm at 50% of the monitoring water points. There are also persistent arsenic problems in specific points of the northernmost area of the aquifer (PHD, 2016). A WEI of 1.3 in Los Arenales and 1.65 in Medina del Campo have driven authorities to specify the order of priority of use as well as the introduction of some additional integrated water resources management (IWRM) measures.

2.2. Response measures to intensive groundwater use

A key goal in the proposed measures of the Duero River Basin Plan, or PHD (CHD, 2016), is to reverse the poor status of water bodies to a good condition. A series of measures were identified which included: establishing limitations on the water withdrawals; recommendations on crop selection; enhancing monitoring activities to track the evolution of water bodies (Art. 62); controlling and/or limiting abstractions (Art. 56) by means of flowmeters (Order ARM/1312/2009); establishing rules for performing MAR operations and promoting the creation of *Groundwater User Communities* (or, in Spanish, *Comunidades de Usuarios de Aguas subterráneas, or* CUAS).

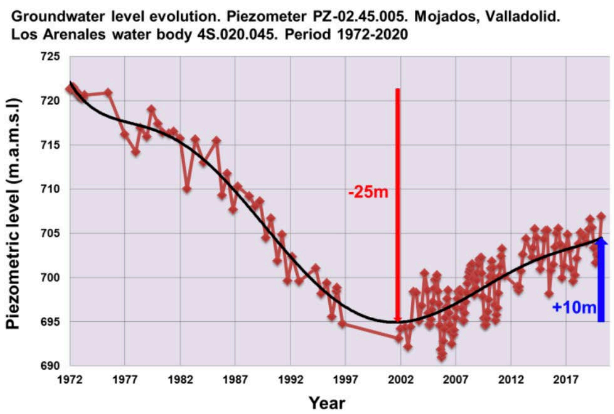


Figure 1-2 *Piezometric evolution of Los Arenales water body (1975-2020) (Source: authors 'own based on open data publicly available from: chduero.es, 2020)position of the selected piezometers and main villages*

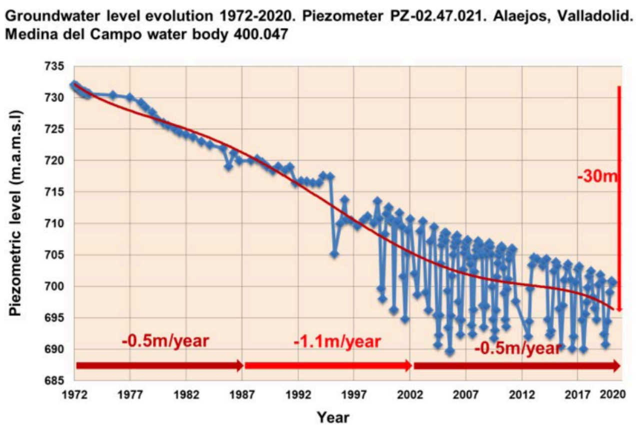


Figure 1-3 *Groundwater level evolution in Medina del Campo Groundwater Body (1975-2020) according to river basin management plan and further monitoring MAR activities have still not been fully implemented. Source: authors 'own based on open data publicly available from: chduero.es, 2020)*

Table 1-1 *Characteristics of the selected piezometers to monitor groundwater evolution of the water bodies analysed in this study*

PIEZOMETER	PROVINCE	PROVINCE	WATER BODY	MAR SITE	X (UTM)	Y (UTM)	Well Depth	Z (m.a.s.l.)	Number of Records
PZ0245005	VALLADOLID	VALLADOLID	DU-400045 LOS ARENALES	PEDRAJAS	362029	4587057	150	721,82	159
PZ0247021	VALLADOLID	VALLADOLID	DU-400047 MEDINA DEL CAMPO	MEDINA	314256	4576503	250,5	733,58	189
PZ425 MAPA	SEGOVIA	SEGOVIA	DU-400045 LOS ARENALES	EL CARRACILLO	365813	4572003	15,5	768,03	49

> *“CUAS include functions such as holding information meetings with the end-users, inviting individual agents to join collective institutions for each groundwater body”*

This paper focuses specifically on the development of a series of MAR schemes and the creation of so-called groundwater user community groups. Both MAR and CUAS will serve as entry points to understand the full system, including other measures. After presenting the specific case study areas, we analyze both measures, looking at the role of co-management for MAR through a collaborative governance model among all stakeholders in the area.

The constitution of the irrigation communities, in our case CUAS, is required by law for water bodies in poor condition. CUAS in the study area require the intervention by the public administration, specifically by the Duero river basin agency. The main actions performed by these CUAS include functions such as holding information meetings with the end-users, inviting individual agents to join collective institutions for each groundwater body, and developing rules to help share groundwater resources in homogeneous zones. Once these initial functions are established, CUAS can invoke formal meetings to create CUAS for each groundwater body. The process ends with the signing of a binding collaboration agreement between each CUAS and the Duero river basin agency, i.e. a public private partnership (PPP). This approach applies and enhances key elements of IWRM. These PPPs enhance governance through the participation of farmers and the population in general in the decision-making processes to increase water security through both hard and soft management measures. The approach ultimately helps create a robust Decision Support System (DSS) for all stakeholders. In this paper we also add people to the equation in what are known as public/private/people partnerships (PPPP).

03

Key questions addressed and scope of the paper

The scope of this paper is to look at intensive groundwater use and how the combination of hard measures, like MAR, combined with soft measures, like the creation of CUAS, can provide new co-management opportunities as spaces for collaboration in Public-Private People Partnerships (PPPPs) for better groundwater management. New PPPPs rely on converting data into valuable information for better shared decision making by all stakeholders. They provide “arenas” that help with conflict resolution through regular interaction among all stakeholders that cement mutual relationships and build social capital.

The main goal therefore is to study how the creation of strong spaces for collaboration between authorities, water users, with the support of technical measures like MAR, combined with good data and science, provides a more robust environment that builds trust (and lowers transaction costs) for better decision making, with positive economic, social and environmental outcomes.

The paper therefore addresses several specific questions that complement and support the central question i.e. how PPPPs can enhance governance for better water security. Related questions are:

- First, what are the main impacts and risks derived from intensive groundwater use? What are the key vulnerabilities identified for our case study areas?
- Second, what are the main barriers to be overcome? What kind of response measures can be introduced to improve the current intensive groundwater management and governance?
- Third, what are the main policy implications and recommendations to boost agricultural development and water security in the area? Could some of these lessons be replicated or transferred elsewhere?

To address these questions, we review the current water management parameters. Also, we analyze the changes that were implemented in the organizational structures, specifically the creation of CUAS. We show how MAR can be a key element for agricultural development and to improve regional water security, and how this must be accompanied by educational and dissemination activities, which are crucial to ensure that these response measures for co-management of conjunctive use of water resources are effective in the long term.

3.1. Hard structural measures to address intensive groundwater use: managed aquifer recharge schemes

Under current law, regarding MAR activities and their associated risks, current regulations specify that all the authorizations for MAR with natural waters will require the constitution of a community of beneficiaries (Art. 66). It also regulates water quality protection measures requiring annual inspection by the authorities and an appraisal of general water body conditions. The on-site inspection is often supported by remote sensing techniques, surveys and indirect pumping estimations obtained from electricity consumption records. Therefore, legislation establishes that any recharge permit will require the setting up of an irrigation community for those users that benefit from licensed large scale river diversion water allowances. Zoning was established according to the exploitation index.

The CUAS effectively are beneficiaries of hydraulic infrastructures built to help maintain favorable groundwater services. For example, the MAR infrastructure set up in El Carracillo and Santiuste was funded by the central government as public investments in the interest of the nation to minimize environmental costs. It is transferred to the CUAS if they commit to take responsibility for the operation and maintenance costs for a 35-year period, while allowing research activities to be undertaken. Thus, local groundwater user group members manage the gates, valves, and other elements, handling their water systems to irrigate crops and the MAR systems. Hard infrastructure was installed to increase the water supply capacity, complemented by capacity building activities run initially by the Ministry of Agriculture.

In terms of physical vulnerability, the area occupied by both water bodies is considered "vulnerable" due to the presence of nitrates in the monitoring network exceeding 50 PPM at five water operation points.

Research and development (R&D) projects have been undertaken in the area through a consensual process with the CUAS. For both MAR sites, capacity-building activities and workshops were developed by the water authorities and researchers while developing the projects. Equally, information and data have been provided by farmers regarding internal water management practices and volumes used. Consequently, a space for collaboration has developed in which both counterparts are undertaking joint activities (see Figure 1-1). In this context, MAR is generating good results thanks to the joint work from scientist/technicians, water authorities and the CUAS and their members.

3.2. Soft non-structural measures: CUAS and wider stakeholder engagement

In relation to what we have called "soft" measures, the creation of CUAS and a "space for collaboration" are based on trust that a fair use of (ground)water resources and organizational measures will be developed. There is an expectation that this commitment to collective action will have a direct influence and be reflected also on groundwater quantity and quality improvements.

Farmers undertake the construction of small structures through their own private initiative, which do not require large investments, e.g., the construction of a collective well, the consolidation of unconnected plots of land from the same owner, and internal administrative agreements to use their water allowance. The key element is the creation of a direct counterpart with the river basin authorities regarding permissions, authorizations, and water-related activities according to the regulations. This sets the ground for a collaborative style of governance.

Trust among the different actors involved is crucial since final agreements equal actions for the protection of (ground) water. However, there are still some actors that can oppose these types of organizational schemes, creating a complex local environment with opposing interests, which eventually can require Court decisions to be resolved. All these actors, despite their apparently opposite objectives, play an important role in the search for a common objective: working towards the sustainability of the system.

In terms of stakeholders, we differentiate three key stakeholders: first, the Duero River Basin authority (or CHD); second, members of the CUAS and water end-users; and, a third group of stakeholders, designated "stakehomers". The stakeholders in this third group are included in the public participation schemes (please refer section 6.3 about the findings of this paper).

3.2.1. The Duero Basin Agency

The CHD was created by Royal Decree of 22 June 1927, with the mission of guaranteeing the availability and quality of water to meet the different uses . It is an autonomous body responsible for water management in the Duero River Basin, dependent on the Water General Directorate from the Ministry for Ecological Transition (MITERD). The main functions of the basin organizations are the preparation of the basin hydrological plan, the administration and control of the public water domain, and the construction and operation of public works. Other duties include: granting of authorizations and concessions (or water allowances); inspection and monitoring of compliance with the conditions of legal concessions and authorizations; the implementation of plans, programs and actions aimed at an adequate management of different legitimate demands in order to promote savings, and the economic and environmental efficiency of different water uses through the integrated management of surface and

C.H.D. STRUCTURE: BRANCHES, ADVISORY BODIES AND COUNCILS

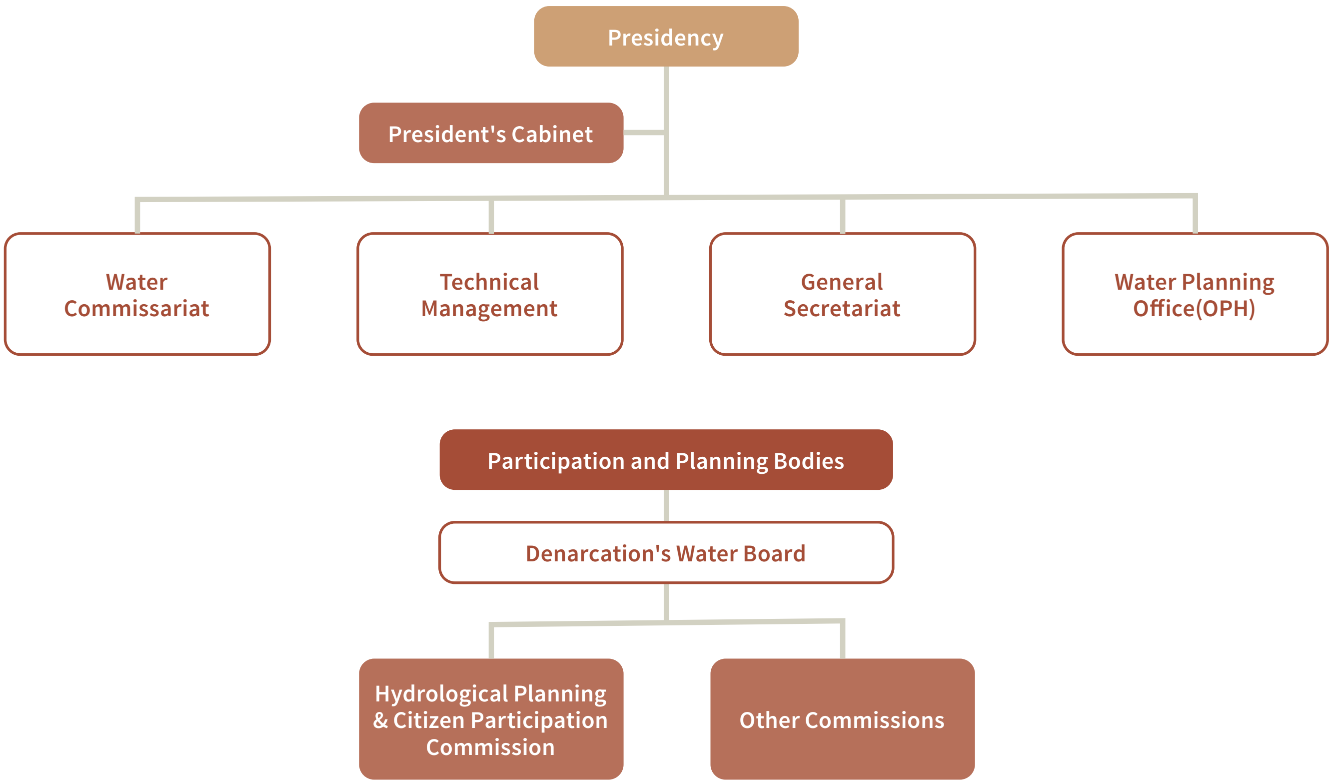


Figure 1-4 *CHD structure, advisory bodies, and councils (modified from https://www.chduero.es/, 2020)*

STAKEHOLDERS ORGANIZATIONAL SCHEME. EXAMPLE FOR AN IRRIGTION COMMUNITY

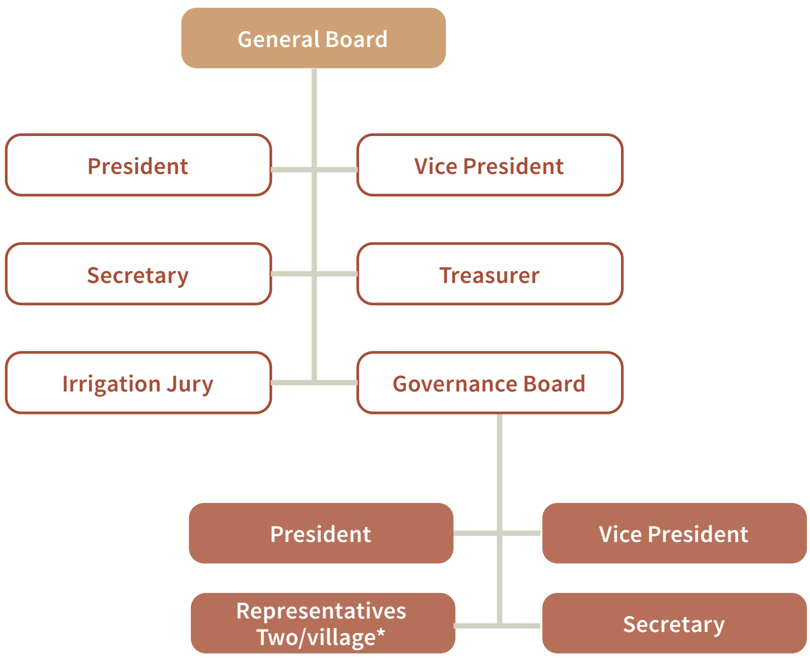


Figure 1-5 *Stakeholder's organizational schemes. Example for El Carracillo Irrigation Community (*one member and one alternate represent each village included in the CCRR´s domain)*

groundwater; and, when requested, provision of advice to the General Administration and even to individuals. The structure of the CHD, the competences assigned to each branch, and its advisory bodies and councils, are represented in Figure 1-4.

3.2.2. CUAS and Irrigation Communities

The Irrigation Communities are regulated by Royal Legislative Decree 1/2001, of July 20th, which approved the revised text of the Water Law, which in Art. 81.1 provides that "*users of water and other goods in the public water domain from the same intake or concession must set up user communities. When the destination given to the water is mainly for irrigation, they will be called irrigation communities; otherwise, they will receive the qualification that characterizes the destination of the collective use*", e.g., groundwater users' communities. The communities of users "water users and other goods" in overexploited aquifers are encouraged to establish internal rules related to groundwater governance. Most importantly for our paper, the Spanish regulation also specifies that CUAS also must be created for MAR: "*all the authorizations for water management and also artificial recharge with natural waters will require the organization of beneficiaries in community of users, a legal entity that becomes the sole interlocutor with the Administration*".

Figure 1-5 outlines the organizational structure of these communities, with only minor differences depending on their size.

Figure 1-6 shows how the power and interest dimensions can affect the roles that stakeholders play in the decision-making process, and strategies that water authorities could adopt. The figure shows the dimensions of power and interest and associated stakeholder management schemes.

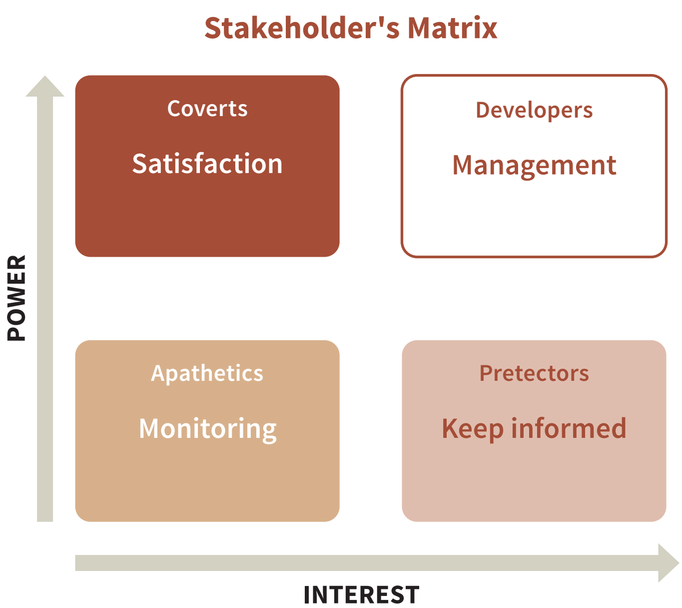


Figure 1-6 *Stakeholder's matrix. (Source: authors' own based on https://www.e-education.psu.edu/earth107/node/1448)*

Stakeholder roles are shown at the top of each quadrant, with management approaches for each role shown at the quadrant's center. Secondary stakeholders become "developers" of the activity (e.g., CUAS in relation to agreements on water use permits) and these have the dedication and ability to easily steer or influence the decision support system and later, the decision-making process. "Protectors", who have high interest but low individual power (farmers) should be kept informed throughout the decision-making process. Finally, low interest but high-power group called "Coverts", for example farming trade unions, should be kept satisfied. Consequently, CUAS are considered a fundamental instrument for water planning, control, and the rational use of groundwater, as will be shown. The water Authorities guarantee that support is given to the setting up of these organizations "once the users are aware of the advantages and disadvantages of their coming together".

04
Methodology

For this paper we have used a mixed methods approach consisting of a literature review and case study analysis which combines primary data, workshops, and interviews (Figure 1-7).

Literature review

The paper draws on literature in the domains of groundwater use, groundwater governance, collective action in natural resources management, managed aquifer recharge and the role of data and information in decision making. The literature review of primary and secondary sources was always informed by our key terms as defined in the GLOSSARY.

Case study approach

As will be described in the next section, the paper focuses on one region in Spain and the collective experience and practical lessons learned from two aquifers with some of the earlier and more extensive MAR experiences in the world. We draw out the main successes and failures of the collective agreements with end-users to address intensive groundwater use. We draw on data collected thanks to a series of European projects on water management (DINA-MAR, FP7 MARSOL and H2020 NAIAD). In all cases, an underlying approach was based on participant observation, aiming to create an "environment of trust" between scientists and the different types of mapped stakeholders. Over time this helped to create a "space for collaboration", enhancing the potential for an integrated water management system. Both the "environment of trust" and the "space for collaboration" were strongly supported and improved through capacity-building activities, which were very important, with several actions performed by the project members.

"Both the "environment of trust" and the "space for collaboration" were strongly supported and improved through capacity-building activities, which were very important, with several actions performed by the project members"

The method to collect information followed four stages (and methods):

- First, collection of information from available sources via Internet and in direct contact with the different stakeholders (river basin agencies, users, and the public).
- Second, collection of information both from water authorities and (ground)water users' communities through face-to-face interviews.
- Third, several open workshops were conducted, involving participants in each territory, also inviting external agents, which included discussion around a structured pre-identified set of themes during these meetings.
- Fourth a series of surveys were distributed to attendees. The information gathered has been studied, compared, and discussed, to obtain sets of recommendations and lessons learned.

Interviews

The four farmers associations were interviewed followed by the hosting of specific thematic workshops (see below) during which an evaluation sheet and a survey template were received from all the assistants. More than 50 interviews and surveys were conducted in these areas (except for the Pedrajas-Alcazarén, where the number of interviews was lower, at around 20 between 2014 and 2020).

In terms of the questions posed in the interviews, some of the most important issues analysed were:

- The physical and other aspects of their plots of land, e.g., area, crops, rotation, subsidies, and grants from the government, etc.
- The organizational scheme for water distribution, what concerns farmers would like to put forward to the water authorities, what infrastructure could be necessary, their agreement with potential land consolidation changes, elements still missing in the case study areas, etc.

Workshops and Follow up surveys

At least six workshops were hosted in each area, coordinated by the authors of this chapter, with evidence also provided through some additional workshops carried out through other projects. Participants included representatives from public Authorities (CHD and JCyL), invited specialist/advisors, scientists, the presence of the mayors of the main villages and the board of each community in all the cases (Table 1-2).

Table 1-2 Summary of the Workshops held in the case study areas

Theme and Project	Number Workshops and Attendees	People attending	Objective	Location and Date
AR4FARM (MARSOL Project)	25 and 40 attendants respectively	farmers and the general population in these agricultural areas	Innovative groundwater "artificial recharge" techniques and experiments, Los Arenales groundwater body current state and overexploitation, building works description, environmental impacts specially on woodlands, water management techniques at user level and recommendations, use of alternative energy sources for irrigation, preliminary and future studies and Works, Modflow developments of both aquifers; irrigation with reclaimed water: the Pedrajas-Alcazarén case.	Santiuste and Gomezserracín (Segovia), October 29th and 30th 2014
MARenales workshops	50 and 60 people	Students and "the population in general	Los Arenales aquifer structure and functioning, technical solutions, benchmarking among the different areas, construction and site investigation techniques, monitoring, wise management of the network, recommendations for cleaning and maintenance (O+M), solar pumping, water and energy saving recommendations.	Coca (Santiuste) and Gomezserracín (El Carracillo) 2015 March 10th and 11th
Regional AR2FARM (MARSOL)	40 and 50 attendants	Stakeholders from Los Arenales aquifer irrigation communities, civil servants from the regional government, river basin authorities and members who claim that MAR is damaging certain ecological values in the zone)	Focused at a regional level; it exposed most of the outcomes achieved from the project regarding MAR as a technique for agricultural development, MAR to address aquifer "overexploitation" caused by irrigation, as well as to tackle the adverse impacts of climate change.	Cuéllar (Segovia), municipality between El Carracillo and Alcazarén areas 2017, March, 28th
NAIAD	30 to 50 attendants	All stakeholders (river basin agency, farmers, scientists, NGOS, civil protection, insurance)	Identification of main perceived risks, key strategies and the main barriers and drivers. Discussion of the main measures for improved IWRM and their simulated impact.	**Arevalo 2017, 2018 and 2019**

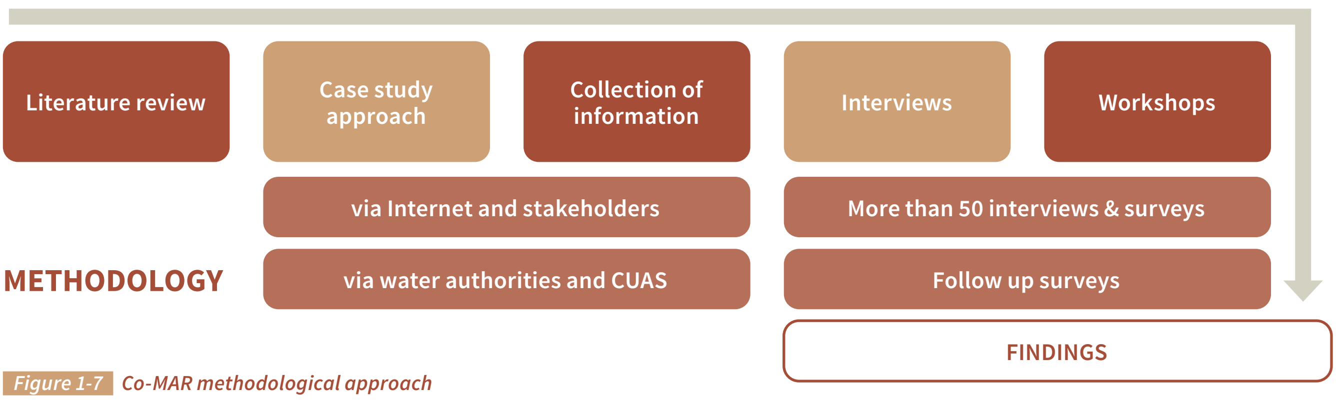


Figure 1-7 Co-MAR methodological approach

05

Case study synopsis

In this section we introduce the case study areas by describing first, the background, second the hydrogeological characteristics, third the current MAR schemes, and finally, the collective agreements to create community user groups to co-manage groundwater resources including groundwater recharge. Refer to Annex 1 for details on each MAR arrangement.

5.1. Background on Managed aquifer recharge (MAR) in the area

We can consider MAR as a technique to mitigate impacts on water quantity due to excessive groundwater pumping. Therefore, there is a logical connection between agricultural development, ensuing potential overexploitation risk and MAR as a response measure. Both of our case study areas, Los Arenales and Medina, are sites where the main driving force of the local economy has been and still is irrigated agriculture, with an increasing water footprint from the regional groundwater exported abroad as vegetables and fruits.

This area became one of the first high agricultural extension areas in Spain and across the world for MAR. Most of these sites count on MAR facilities that provide between 22 and 25% of the total amount of water used for irrigation.
The MAR approach was a response to the evolution of the groundwater level at Los Arenales aquifer from 1972 to 2002. An accumulated decline of 24 and 25 m was registered in parts of the aquifer, such as La Moraña and Mojados (Figure 1-2). For the Medina del Campo water body, the situation is even more complex, with a groundwater decline of 30 m (Figure 1-3) and an exploitation rate with respect to the recharge rate that exceeds 75%. The central government responded, in this case the Ministry of Agriculture, to implement MAR for the “general interest”, and in conjunction with the regional government, to establish regulated limits on water use, the compulsory constitution of groundwater users’ associations as cooperation entities with the central administration, and the development of the so-called “artificial recharge” facilities to reduce the observed impacts of intensive groundwater use.

At regional scale, in 2002 and 2003 the MAR systems at Santiuste basin and El Carracillo District started working, respectively, with some small later extensions, supported by the regional government of the Junta of Castilla y León. the El Carracillo MAR system was further enlarged in September 2015 and included in the Duero River Basin Plan (CHD, 2016), diverting some of the water from the Cega river, a tributary of the Duero river, to the MAR structure. The scheme also established minimum environmental flows while allowing some direct extractions for irrigation along the river course. The Duero River basin Plan, in the first and current second river basin planning cycles, has progressively considered MAR to be a useful water management technique,. MAR facilitated operations, including the consideration of an ecological flow-rate, and thus has been included in new regulations:

5.2. The Hydrogeological characteristics of the Los Arenales and the Medina del Campo aquifers

This section describes the physical attributes of the areas of intervention, most of which share common hydrogeological features. The Los Arenales aquifer (Water Body 022.045) is a large groundwater body that occupies 2,400 km^2 of Castilla y León, with 46,000 inhabitants in 96 villages. The aquifer consists of two aquifers, one above the other. A quaternary shallow aquifer consisting of a fine dune sand layer, alluvial deposits and clay with a 20 m average depth and a maximum depth of 45 m (MARSOL, 2016b). Underneath lays a deeper Tertiary detrital layer (Facies Cuestas) of low hydraulic conductivity. This scheme is equivalent to the neighboring Medina del Campo water body, a different portion of the same aquifer. There are also occasional mudstone outcrops from the Miocene.

“There is a logical connection between agricultural development, ensuing potential overexploitation risk and MAR as a response measure”

The Medina del Campo aquifer (Water Body code 022.047) is adjacent to, and west of, Los Arenales Water Body (see Figure 1-1). It has an area of 3,627.70 km^2, involving part of five different provinces. Medina del Campo also has a high level of groundwater abstractions for irrigation. The system benefits from groundwater dependent wetlands, which act as a natural regulation mechanism with high additional environmental value.
The Medina del Campo water body (code GB DU-400047) has an estimated available renewable natural resource of about 50 Mm^3/year, with a level of groundwater abstractions estimated at 137 Mm^3/year; and with returns and recharge estimated at around 33 Mm^3/year. The irrigated area is 8,896 ha, with an average allowance of 6,000 m^3/ha/year and mean extractions of 53.38 Mm^3/year. The poor chemical quality for the first case (Los Arenales), and the intensive exploitation for the second (Medina), means that it is not be possible to cover all the demand for urban and agricultural water with available groundwater resources.

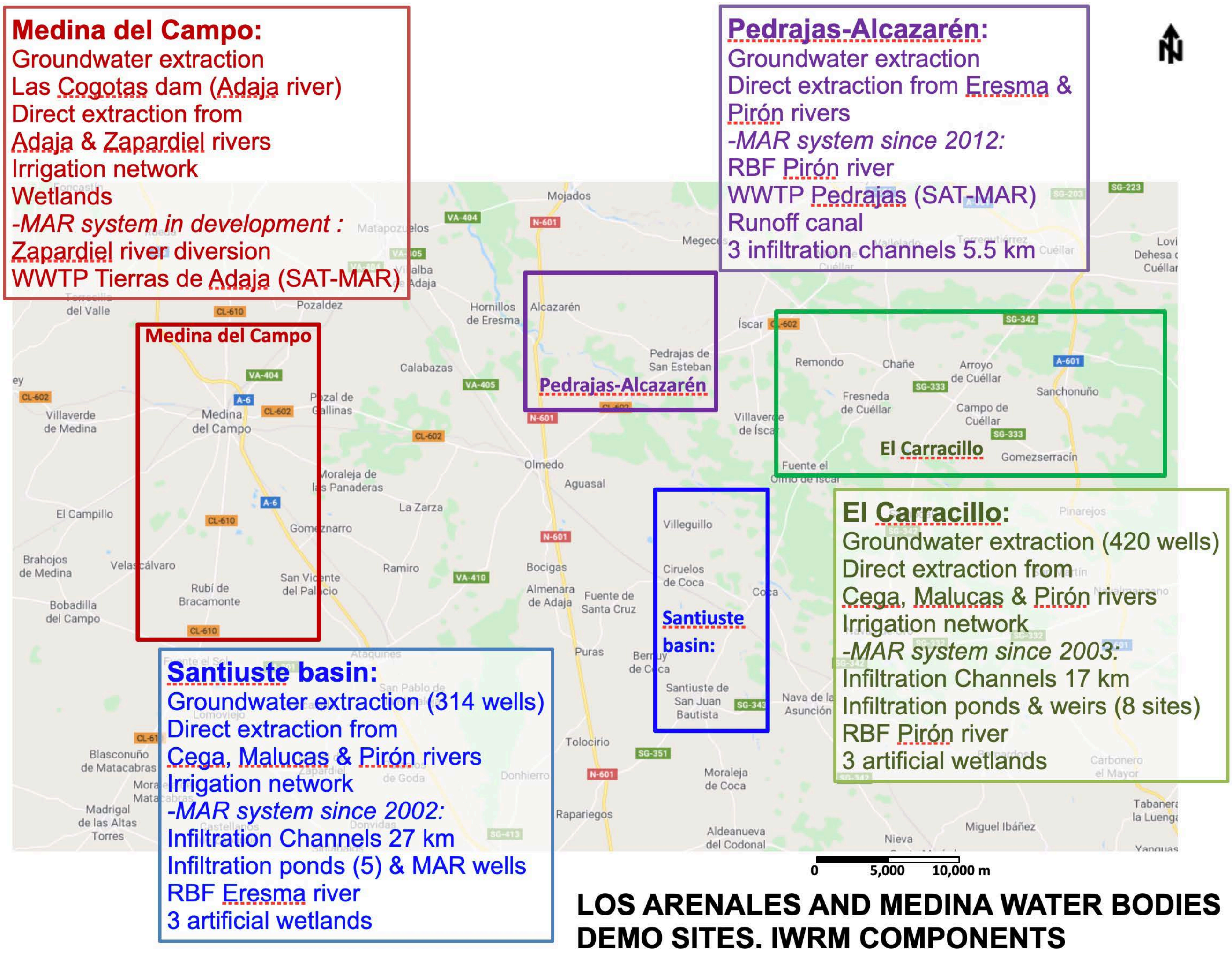


Figure 1-8 *Case study sites and their IWRM main components*

5.3. The Managed aquifer recharge schemes in the Carracillo and Medina del Campo

To address the problem of groundwater intensive use, one of the initiatives from the Spanish Ministry of Agriculture and the Regional Government (Junta de Castilla y León) was to start a series of demonstration projects for MAR: first in the Santiuste basin area in 2002, second in El Carracillo in 2003, third in the Alcazarén-Pedrajas in 2011 and finally in the Medina del Campo area in 2019. The MAR system targets the Quaternary aquifers in all cases.

In line with integrated water management techniques, a series of projects were developed for MAR based on the diversion of water surpluses from a river, and their infiltration by means of canals, infiltration ponds and high diameter wells. In addition, two other sources were also considered, with the runoff conducted through a specific channel and eventual water transfers from the Pirón river.

All these systems share “MAR-based” solutions to address aquifer-intensive use that are characterized by five common features: 1) passive systems that do not require electricity for MAR activity, relying instead on gravity); ii) intermittent recharge, i.e. it takes place when there is high flow in the rivers from which water is diverted; iii) a regulated MAR system which is integrated into the whole IWRM scheme; iv) legally regulated through water permits with specific characteristics, and v) integrated, with interconnection of all the water management options of surface and groundwater origin. Figure 8 depicts these five main elements, and how each was incorporated into the MAR systems.

The main differences for each MAR system are based on the origin of the water. The El Carracillo District MAR system relies on water from the Cega river, generally during the rainy season (winter-spring). The Medina del Campo system is about to begin a new MAR system with water diverted from the Zapardiel and Trabancos rivers (which eventually overflow certain agricultural areas around the city) and are used for MAR by means of infiltration ponds and canals. The Santiuste Basin MAR system relies on water surplus from the Voltoya River. The Pedrajas-Alcazarén scheme relies on a wastewater treatment plant (WWTP), so the water supply is available 24 hours and 7 days a week, also capturing runoff water from the village across a specific channel and eventual diversions from the Pirón river.

5.4. Groundwater community user groups in the Carracillo and the Medina del Campo aquifers

The CUAS are equivalent in function to Irrigation Communities (CCRR) but with two main differences. First the terms of irrigation community and groundwater user community have subtle but important differences based on the origin of the water used. In cases where water withdrawal nears 100% of groundwater sustainable yield, the correct term is CUAS instead of CCRR. Second, as communities, CUAS are in principle open to other users, not just irrigators. However, for operational purposes (i.e. for negotiation with the Authorities), both types are equivalent, acting as a collective and unique (legitimate) voice with the water authority of the Duero river basin agency. However, for reasons of tradition and historical practices, farmers often choose to set up as “irrigation communities”. In our case study areas, we therefore have communities called groundwater user groups and irrigation communities, although technically all of them are CUAS.

In the case study area, there are four CUAS selected and studied. Their organizational structure is the same with some slight differences (see Figure 1-5).

- The El Carracillo irrigation community (Los Arenales water body).
- The Cubeta de Santiuste irrigation community (Los Arenales water body).
- The Alcazarén association of commoners or water users’ association (Los Arenales water body).
- The Medina del Campo irrigation community (Medina water body).

*Table 1-3 Irrigation communities´ areas. Comparison data for 2020 *Figures only available for the whole water body*

TOPIC	El Carracillo	Medina Campo	Santiuste Basin	Alcazarén
Inflow (Mm³/year)	3,110	83*	*inflow 34 / *outflow 54	
Outflow (Mm³/year)	14.008	137*	8.019	1.19
Water Exploitation Index (WEI)	1.3*	1.65	1.3*	1.3*
MAR facilities construction. Initial cost (€)	5,273,999	Studies in progress	3,948,079	2,200,000
Hectares in irrigation	3,500	8,896	790	400-520
Hectares in irrigation before MAR activities began	3,000	35,000	515	n/a (<400)
Arable hectares	7.586	45,116	3.061	1.593
Number of commoners in each irrigation community	713	In the process of being formalized	440	190
Total volume employed for MAR since intentional recharge began until 2020 (Mm³)	31.47	0	33.98	0.287
Years of operability until 2020	18	0	19	9-10
Ratio recharge/ total surface (m³/ha)	24.18	n/a	65.59	0.18
Average annual groundwater extraction (Mm³/year)	8.0***	137	0.21	0.06
Contribution to irrigation groundwater proceeding from MAR activity (m³/ha)	314.3	Incipient	852.6	1.500
Percentage of water used for irrigation proceeding from MAR activity (%)	23.8	0	27.84	25.99
Rise of the average groundwater table attributable to MAR (m) until 2015	2.3	0	1.47	0.75
Energy savings attributable to the rise of the groundwater table by MAR (kW h/m³)	0.165	0	30.4	18
Maintenance and operation costs per cubic meter of “MARed” water (€/m³)	0.08	0	0.05	n/a

As stated earlier, CUAS are a real embodiment of a PPP since they are by law public legal corporations in which the users collectively manage the water use rights they have been granted, having to report to the water authority on this water use. These are communities that bring together one or more municipalities and must have more than 20 members. These communities define their respective area to be irrigated in rotation, which exceeds 20,000 hectares. The first CUAS was Cantalpino (Salamanca), created in 2014. According to CHD data, the 39 communities are in Medina del Campo (5) and Los Arenales (18), Tordesillas, and the rest share transboundary water bodies (Figure 1-11).

Most of the irrigated areas range between 400 and 5,000 hectares. By 2018 the Duero river basin agency had started the process of formally constituting the 39 Groundwater Users' Communities (CUAS) in the provinces of Ávila, Segovia, and Valladolid. In addition, there are another 71 with less than twenty members, which were also established in 2018, indicating a level of institutionalization across the basin.

The CHD has actively supported the constitution of groundwater user communities as the appropriate instrument to facilitate collaboration, control and to plan the rational exploitation of aquifers, as required by the new water policy which includes co-management as a central principle. The objective is to have at least one water user community for each groundwater body. The CHD considered that the most effective way to achieve this objective was the creation of so called "base communities" in one or more municipalities (between 2,000 and 4,000 hectares of irrigated land), which are then subsequently grouped in a central Board as a CUAS. The data of these CUAS has been included in Table 1-3.

Table 1-3 summarizes the most important data for the case study areas, including information on the CUAS (e.g., number of water users) and MAR data. This table also includes recent water balances and management figures that will be discussed in the next sections.

As can be seen from Table 1-3, MAR has increased the number of hectares in irrigation, but more importantly, it has secured a good technique to help address the previous intensive exploitation of the aquifer.

06

Discussion: risks, impacts and responses

This section will identify the main risks, the impacts that the area has experienced, and the main responses to address these risks, giving special attention to the implementation of a socio-technical system: co-managed aquifer recharge. A collaboration space was created to find PPPP solutions to start a gradual reversal of overexploitation, towards the sustainable use of groundwater resources to help secure the area´s long terms agricultural development.

"A collaboration space was created to find PPPP solutions to start a gradual reversal of overexploitation, towards the sustainable use of groundwater resources to help secure the area´s long terms agricultural development"

Departing from the experiences gathered at the four demonstration sites, several responses are identified and discussed to improve governance and enhance regional water security. These are not exclusive to the study area; many of the lessons learned are based on experiences and some general principles that, once adapted to fit the local area, could be extrapolated to similar cases.

We will highlight the main impacts and risks detected during the last 20 years of intensive groundwater use in the area, including the vulnerabilities affecting the system, and the experience gained from responses to make the overall system more resilient.

6.1. Risks

The area is mainly facing three types of risks: problems related to water quantity and over abstraction; problems related to water quality; and, problems related to conflict between stakeholders due to competition over resources. The effect for example of MAR on the water quantity risk is reflected in Figure 1-9 for a piezometer at El Carracillo.

It is essential to understand in detail the hydrogeological features and hydrodynamic characteristics of the area to obtain an accurate water balance for each water body to implement MAR activities. At present there are environmental flows set by water authorities, which is about 20% of the mean annual flow to be respected by all stakeholders. This volume is to protect the river biodiversity, riparian vegetation, and associated wetlands. It also ensures water availability for users downstream such as urban/industrial supply, hydro-electric power generation, etc. In the case of Los Arenales aquifer, the river basin agency (CHD) established technical criteria for a minimum downstream “E-flow” which varies from one year to another depending on precipitation, to help determine the water diversion volume during the wet season.

In relation to water quality, there are groundwater areas with nitrates and arsenic concentrations that exceed the legal limits. In the case of arsenic, the cause is attributed to the weathering of tertiary geological materials with arsenopyrite nuggets. There has also been some presence of free arsenic in groundwater linked to the use of fertilizers, pesticides and additives used in cattle feed. Some environmental groups have also mentioned the generation of arsenic in combination with iron ox-hydroxides which are introduced to the aquifer through agricultural activity (data based on surveys but without written technical references). These allegations have been officially presented to the Authorities, hence there are some areas of conflict in relation to both water quantity and quality, with competition over water use as a conflict of interest for which collaboration helps as an important element of PPP and DSS.

6.2. Identified impacts due to groundwater intensive use and related extraction and/or diversion of water from rivers

There is a groundwater table decline in the affected areas (Figures 1-2 and 1-3) which can in turn trigger failure to modernize extraction wells. Also the situation increased end-users’ water exploitation costs. From a physical point of view, the modification of the unsaturated zone can lead to compaction of the terrain, and the creation of isolated compartments in the aquifer. It can also lead to possible water quality deterioration, such as salinization due to recirculation from a modified water cycle. Some indirect impacts are also worth mentioning, including: the salinization of the soil in cases where watering doses are not applied after irrigating the crops; potential progressive desertification in the area; eventual geotechnical problems such as subsidence, terrain collapses, landslides in the slopes and terraces next to rivers; local modifications in the hydraulic parameters of the aquifers; and, diffuse pollution from agro-chemicals.

On a larger scale, modifications to the natural river-aquifer relations and in the river’s surface water regime will eventually affect drainage networks, man-made infrastructure and groundwater dependent wetlands. Also, from a governance point of view, legal problems arise from impact on third parties’ rights, e.g. fishermen and electricity generation facilities, which generate a potential conflict with irrigation communities competing for the use of river water, and where a “cascading effect” arises.

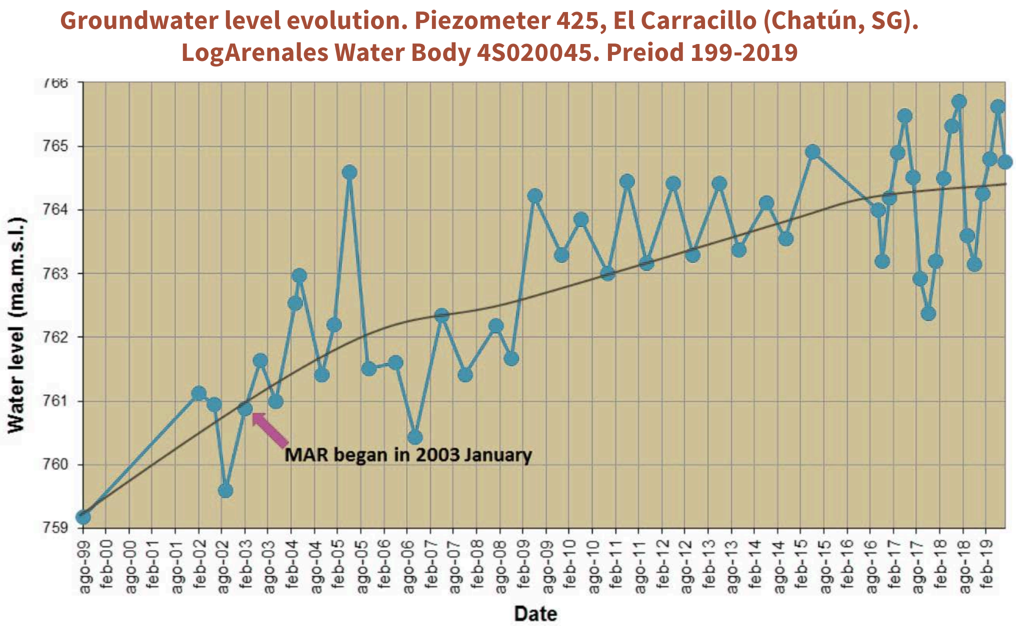


Figure 1-9 *Evolution of the groundwater level in El Carracillo, piezometer MAPA-425 (Chatún) from 1999 to 2019. MAR began in 2003*

6.3. Discussion on response measures

We will now discuss the main response measures looking first at the implementation of MAR schemes as hard structural measures. Second, we will re-visit the onset of CUAS as soft non-structural response. Third, we will contextualize this co-management of recharged aquifers with a series of policy instruments that act as additional levers to shift the system gradually towards a more sustainable keel.

6.3.1. Managed aquifer recharge

MAR has played an important role in mitigating aquifer over-exploitation. The recovery of the water table level has had a direct beneficial impact with lower energy consumption from wells pumping, and therefore, a reduction in the electricity or fuel cost. MAR activities have also had a direct effect on better quality crops with higher yields, higher income, and easier market access. MAR techniques are also interesting for reducing floods by storing excess water.
The continuous monitoring of the SAT-MAR activity in Pedrajas-Alcazarén, where reclaimed water is being used for aquifer recharge, shows that no serious impacts have been detected so far in groundwater quality.

According to the Agricultural Technology Institute of Castilla y León (ITACYL) and survey results summarized below (Table 1-4), MAR has socio-economic benefits, while helping to fight aquifer overexploitation. The contribution to groundwater irrigation from MAR activity is about 24%. The cost per cubic meter of water, in relation to the initial investment, is becoming gradually more affordable (about 5 €/m^3).
In relation to environmental impacts, the groundwater table has risen (Table 1-3) and most of the water dependent wetlands are recovering their ecological function, except for the Medina site, where the wetlands are still in a process of regeneration (at the time of writing, the lagoons were dry with the water table about 3 meters below the bottom).

MAR schemes have generally been considered in the "general interest" of the nation. The river basin authorities are responsible to manage water quality and quantity, and for granting the relevant permissions. The economic-financing regime, the authorization process, and a number of control mechanisms also required modifications. A summary of the actions that need to be carried out for the implementation of MAR systems is presented in Figure 1-10. What is important for co-management is that a Co-MAR scheme grants specific rights, e.g. that beneficiaries are obliged by law to maintain the infrastructure. Thus, users become directly involved in the management and maintenance of MAR facilities to ensure its appropriate operation and maintenance to ensure irrigation occurs with good quality groundwater (i.e. with reduced nitrates and arsenic).

There has, however, been a level of conflict with some stakeholders with important disagreements among different agents. The most important is a conflict of interest between ecological groups known as "river defenders", fishermen and two mini-hydroelectric power stations situated downstream from the MAR water diversion. Together all consider that the extraction of water from the river is excessive.
Several meetings and workshops have been hosted, organized by political parties, partners of European projects and local municipalities to discuss the different points of view. There are three main visions: one group defends an increase in the cultivated land; a second group prioritizes services for the rural area like the acquisition of high-speed internet, the

Table 1-4 Some indicators for MAR outcomes (Source: MARSOL, 2016b)

	Region of Castilla y León	Municipalities in the case study areas
Density of working age population (unit: inhabitants between 20 and 64 years old per square kilometer)	7.4 inhabitants./km^2	17 inhabitants/km^2
agroindustry (unit: related jobs workers per square kilometer)	3.73 w/km^2	11.29 w/km^2.
Number of companies in the area (Unit: nº of companies per square kilometer)	0.46	1.28
Population growth	-6% decrease in the region -	+28% increase since MAR began

construction of a hospital in the area, and a diversification of economic activities like agricultural tourism and minor hunting (a broader rural development model); and a third group advocates for a larger environmental flow in rivers. This last group has come into conflict with the first group. From meetings held, there have been two important conclusions. First, the availability of water cannot satisfy all interests, even more because the issue is compounded by the drought period over the middle of the decade.
Second, farmers' associations and groups that are opposed to the construction of new MAR facilities have one thing in common: a desire to protect the environment and the general interest. Therefore, water authorities have played an important role as mediators, stating that "administering misery is really complicated", talking about the available environmental flows during the last drought period when parties were blaming each other for water scarcity. In the case of El Carracillo, the conflict has now gone to the courts, where the outcomes will be decided shortly. A court decision is needed to find an agreement between the environmental flow, farmers' demands, and a possible compensation for affected hydroelectricity suppliers. The importance of these different points of view and interests are crucial to the overall sustainability of the whole system. The "space for collaboration" and the "environment of trust" among these actors will continue to deepen from these mediation and conflict resolution actions to address the real tradeoffs that need to be resolved on the path to a less groundwater-intensive development model. These tradeoffs can be softened due to the benefits from MAR and collaboration efficiency/equity gains. All parties, despite differences, share a common target: the sustainability of the system.

6.3.2. Creation of CUAS for MAR co-management

Here we analyse the creation of the CUAS, their main role and their main outcomes. In terms of CUAS creation, the farmers' willingness to form an association depended on two main factors: first, the farmers' risk awareness; and second, the requests from the authorities, especially the river basin agency, to have a legitimate counterpart with a single voice for negotiations. The Duero water basin authority has preferred to create smaller CUAS with 15 to 20 farmers, a good size to negotiate collective water management rights due to the ease of handling smaller groups and their lower capacity to exert pressure. There are two levels of interaction between the water authorities and the CUAS.
The first level is the one of the representatives, with meetings between representatives from the water authorities and the representatives of the end-users; this level entails classic negotiation dynamics. The second level, which is also critical, is the fluent communications with decision makers from the top to lower ranking end users, with the creation of an environment of general trust to achieve results within a constructive environment. Since the CUAS were created, there have been important changes and lessons learned, often coupled with a change in stakeholder mentality.
Now real public participation, which is a novel concept, occurs on a regular basis channeled through the CUAS.

The main role of CUAS is very relevant in certain issues, such as the rearrangement and negotiated distribution of water availability, energy management, the operation of high efficiency irrigation systems, and the optimization of the irrigation equipment, technical support (e.g., for the correct sizing of pumps), etc. The CUAS' engagement translates into water and energy efficiency savings, especially due to pumping since the water table is higher and the required energy to extract groundwater is, consequently, lower.
An example is the case of El Carracillo District, where the water level rose by +2.30 m due to the intentional aquifer recharge during winter. The economic savings are estimated at around 12 to 36% of the energy cost, depending on the specific site (UNESCO, 2020).

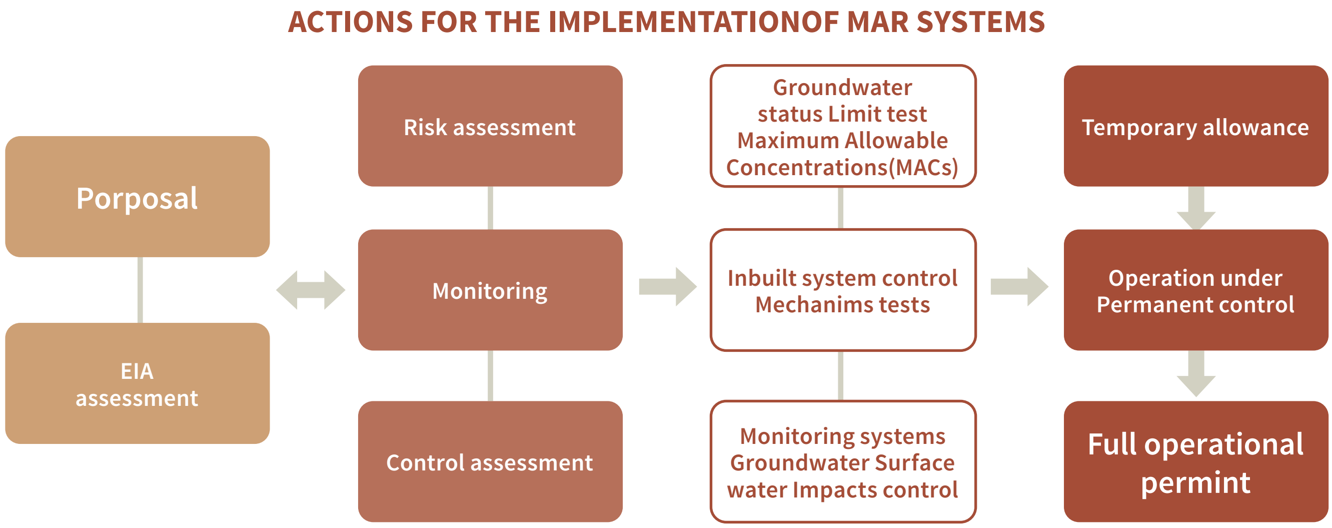


Figure 1-10 Stages to implement a MAR system (Source: authors´ own)

In terms of outcomes, these MAR experiences help on the one hand to address groundwater over-exploitation and on the other to secure the irrigation of arable land.
Therefore, MAR has supported agricultural development, promoting sustainable water resources management schemes, and the subsequent increase in agricultural production due to a greater water availability for irrigation, and thus economic growth in these cases.

Finally, in terms of lessons learnt, it is worth to point out, first, the importance to work on the cooperative nature of the relationship between decision-makers and secondary stakeholders (in our case farmers). Actors need to be better involved in the process, with shared information within the network and decisions taken collectively. Second, access to reliable public information improves trust in the water authorities (CHD) and their management of the water rights process is a critical element for transparency. In turn, once this trust is built, the river basin agency can delegate a level of control over the territory and corresponding groundwater bodies. Third, on a technical note, those old wells that have been abandoned for diverse reasons might be included in the MAR system, applying slogans such as “Do not close a well, reuse it” and the evidence that communities operate IWRM and MAR facilities more effectively than individuals. Therefore, the irrigation communities must be part of, and even the main contributors to, the operation, maintenance, and conservation of MAR devices (ideally with access to expert advice). Fourth, the importance of good information and dissemination materials, like maps, panels, or brochures, informing groundwater users on the aquifer, money saved thanks to MAR activities (electricity, pumping cost, etc.), and any additional income generated need to be displayed and communicated. Co-managed MAR thus has provided an opportunity for agricultural development, which requires careful and expert management, as well as regular monitoring and evaluation in order to help users to constantly reflect and learn from their experiences.

6.3.3. The centrality of water rights for co-managed MAR

The water rights management process is critical. Most of the involved farmers often considered the process unfair and not fully transparent. This widespread perception acted against collective action by all farmers and thus impacted on the potential to reduce groundwater intensive exploitation because users opted to act individually rather than in the pursuit of their collective interest. This is where CUAS can play a central role by creating a space for collaboration, helping to avoid individualised actions by creating a sense of community and thus enhancing the general perception of farmers as part of a wider group. Dissemination activities, workshops and agreements with the river basin agency help to cement this trust and collective action.

In general, MAR activity is performed by the CUAS where they are the MAR beneficiary. This means that, in theory, all members enjoy water use rights. There are some problematic issues, such as complaints that all users “pay a similar fee” yet the amount of water used can vary according to the different uses of groundwater. There are also concerns because “MARed” water also benefits agents who do not participate in the CUA, but who extract recharged groundwater from nearby sites. In fact, reality is complex, and every case must be studied separately. A key solution might be a water rights review granted by the river authorities under technical criteria, which are annually reconsidered.

Several specific issues arise that highlight the complexity of managing MAR water, as elaborated following. First, the Duero River Basin Plan (PHD, 2016) comments on the complexity of merging rights for the conjunctive use of surface water and groundwater, even when extractions are taken from the same aquifer or water body. The collective use of surface water is complex because these permits are processed by different branches of the river basin authority. The legal complexity, therefore, is in the hands of civil servants, and farmers can concentrate their full attention to comply with the law, avoiding cumbersome procedures.

Second, there is a need for transparency. It is a basic water management principle that “water must be assigned under clear criteria and transparency”. These processes must be accessible for the civil society and for those institutions related to water governance, to minimize possible conflicts (López-Gunn & Rica, 2013). Active participation mechanisms that involve the general population in water management issues, either directly or by means of CUAS, need good internal reporting to bring a level of transparency through this active participation and oversight.

Third, most of the farmers are not landowners but rather tenant farmers. According to the Spanish Water law, the private use of groundwater to irrigate is reserved exclusively to the owner of the plot. This mandate can however be circumscribed in the case of CUAS with an internal structure, a suitable organization qualified to limit the use of groundwater according to legal mandates. Also, there is discussion of a policy reform to decouple land property and the right to irrigate, to disentangle certain applications by means of integrated water management solutions.

Fourth, there are opportunities to combine “carrot and stick” incentives. The river basin agency can use the “stick” of threat of forcing farmers to create CUAS if the aquifer is declared to be over-exploited under Spanish law. CUAS in general offer a venue also for “carrots” of positive incentives to farmers, like how to enhance the individual and collective benefits for belonging to a CUAS structure. For example, benefits include clarifying the individual obligations regarding flow meters (acquisition, installation, maintenance and obligation to report the results), transparency of economic contributions to the association, the canon for the use of water, what is a public domain, etc. The case of Los Arenales is interesting because through consensual agreement, the collective water management in this aquifer now relies on CUAS.
The CUAS has helped to reduce the number of users who own small plots of land and users now share a common well or borehole to irrigate their lands.

6.3.4. Access to information

An important element for co-managed MAR is having good access to technical information, ideally in almost real time, for example on the groundwater level fluctuations.
At present access is difficult to individuals because it requires a specific and written information request.
There are two main issues: first, the type of data that could be made available and second, easier access to data.
Wider availability of groundwater status information for the group is expected to have an impact on farmers' risk awareness, enhancing their active participation in decision making, including a wide range of issues like: crop changes, water efficiency, energy systems, land consolidation, the construction of collective infrastructure (dykes, boreholes, small dams), the assignment process, agreements on the use of common structures, irrigation canals (called "caz" in the local terminology), irrigation timing and proposals for the construction of new collectively-owned elements.
For easier access to local groundwater-related data and information, new digital technologies are crucial, including mobile applications, websites displaying the monitoring network information, etc. Many CUAS often require advice from external stakehomers (see Wider stakeholder engagement below), the Regional Authority, and eventually, specialized research centres.

6.3.5. Economic instruments and incentives

Generally, for intensively used aquifers, water authorities avoid establishing variable tariffs for users, preferring fixed fees and/or specific restrictions for the different zones.
Some authors have analyzed other options such as water banking, cap and trade mechanisms, payments awarded in case users reduce their water consumption, the purchase of water extraction rights and/or closer cooperation among the end-users of the resource (López-Gunn & Rica, 2013).

Economic instruments to be considered and applied between water-users and authorities can include:
the purchase of rights to reduce demand; the establishment of an environmental tax to reduce groundwater abstractions, as a method to internalize part (or all) of the environmental cost caused by over-exploitation; and, the constitution of water banks among users. MAR is interesting because it enhances the concept and physical possibility of a "water bank", which could help reconcile the interests of farmers with the recovery of the aquifer. However, compliance with the water use restrictions would reduce the agricultural incomes in cases where no compensation measures were approved. Yet these compensatory payments themselves could be controversial since the abstractor-pays principle should apply. The integrated approach of IWRM recommends a combination of some of these different options and instruments having synergistic effect to reduce the intensive impact of groundwater over-exploitation.

For the specific case study of Medina del Campo, the cost-benefit analyses of the different strategies compiled the assessments of the following types: i) the direct costs of

LA CHD tramita la creación de 39 comunidades de usuarios de aguas subterráneas

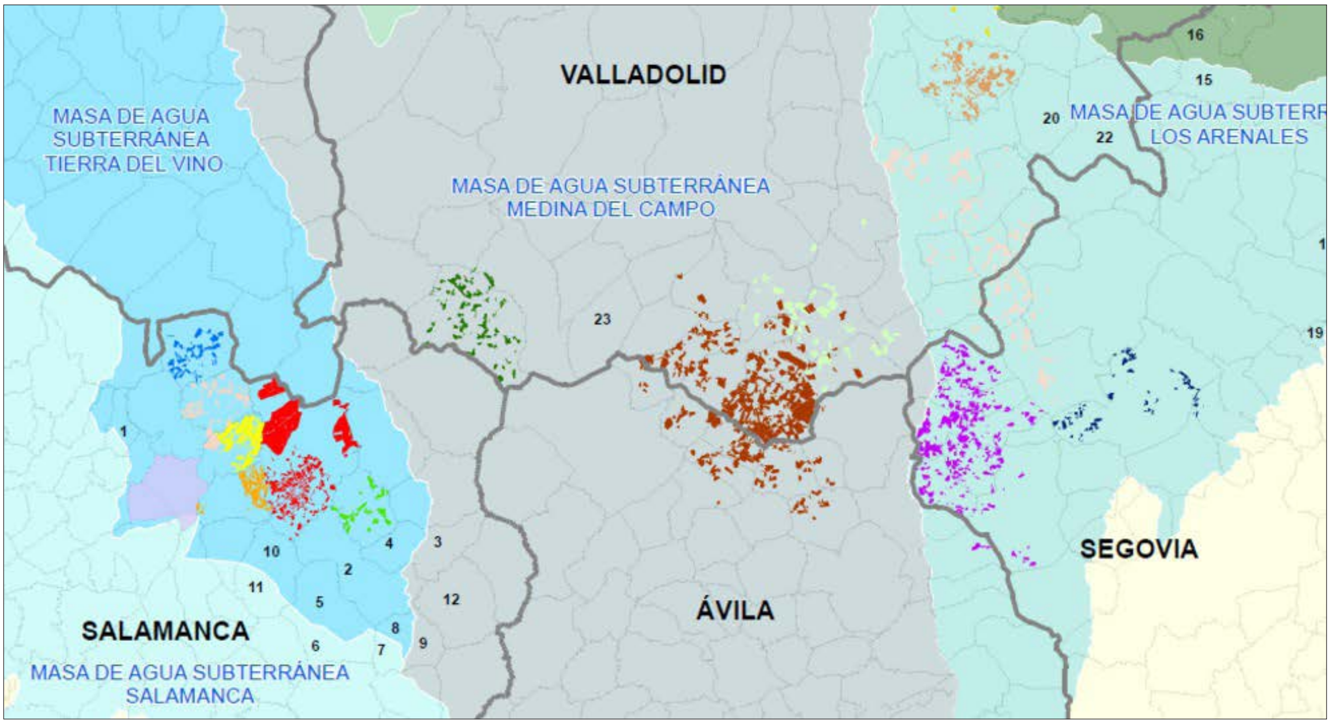


Figure 1-11 News in the Media: Duero/Douro Basin Authorities process the creation of 39 groundwater users' communities, https://bit.ly/2EMLlqf

implementing these strategies; ii) the opportunity costs of the proposed strategies; iii) the costs of the damage due to exacerbated effects of natural hazards (droughts and floods) reduced thanks to MAR activities, which reduce the amount of flood water during extraordinary events, storing a part in the aquifer; and iv), the provision of ecosystem services (Mayor *et al*., 2020) and Nature Based Solutions (NBS).
The incorporation of climatic uncertainties due to the current climate change forecast and trends would increase the exposed risks and their eventual impact.

6.3.6. Public participation and capacity building

From the point of view of participation, it is necessary to maintain and increase the channels of communication, while avoiding very technical language. Also whenever possible, exchange of international experiences should be facilitated, with the aim of sharing criteria, results, experiences, etc., including both the negative and positive lessons learned.
For example, a lesson learned from all capacity building and public participation activities is that local level teachings are more interesting to attendants than general IWRM knowledge. These lessons are particularly interesting since they relate directly to the stakeholders' current situation and to the future evolution in local areas, and impacts of possible changes. There was less interest in past events.

Formally the river basin agencies have two types of venues for the public participation process: the "citizen participation commissions"; and, "other commissions" including CUAS (see Figure 1-4). Both allow a fluent and direct communication with decision-makers. The frequency of the meetings and the communication channels are decided by mutual agreement. It is important that CUAS users´ representatives dedicate time in their usual busy schedules, and that there is adequate representation with a good understanding and knowledge of the process and substantive content.
These public participation processes are important because they can influence future regulations, not only at the preliminary stage, but also during the compulsory stage of public consultation, as marked by law and the presentation of claims. There are other more political channels to influence e.g., regulations and decisions like communicating directly with the provincial representative in parliament.
This had results previously, when, in 1995, farmers visited their representative for Segovia province, Ms. Loyola de Palacio, who in turn defended MAR implementation in the High Chamber. Later in 1996 she became Minister of Agriculture of Spain.

From the point of view of capacity building and training, it is also important for end-users to acquire a basic knowledge of hydrogeology by means of capacity-building workshops. The existence of independent groundwater agencies involved in the groundwater management process has been practiced elsewhere, e.g., in the Netherlands and Israel.
A problem arises from the potential lack of continuity, for example the potential interruption of some lines of action planned as part of European research and development (R&D) Projects activities. Therefore, it is critical to disseminate collaborative experiences, best practices, cases of success and failure, to ensure the support of the general population. With the right information on innovative options, support can be built for a new opportunity versus traditional measures like dams, which are increasingly costly, very controversial and socially divisive.

6.3.7. Wider stakeholder engagement: Stakehomers

Among the public participation agents, authors have proposed a term, adding to the term of stakeholders with so called "Stakehomers". Stakehomers are a group of agents that represent the local population, researchers and people involved in the development of the systems (not in the management), who participate occasionally through legal public consultation or communication channels, including social networks. These are usually individuals classified as the "general population", who can bring new contributions without being one of the agents directly involved (or that has a direct "stake" or interest) in the negotiations.
This stakehomers group can include for example, technicians, associations, professionals, external consultants, cooperation and/or conservation agents, influencers, local leaders, students, etc. Participation by this group is in line with the Water Framework Directive, which entails the promotion of new water policy tools, including public information and citizen participation under Art 14.

Regarding capacity building, each community of irrigators and/or groundwater users has a secretary and an agronomic engineer to help with the main issues that arise and to support important decisions. The communication between the "stakehomers" and the secretaries/board has been excellent since each side is aware of their common interest and friendly interaction benefits both sides. The key element has been the close bidirectional communication between stakeholders and stakehomers. It is important to point out that capacity building activities have been bidirectional, thanks to the regular feedback received by farmers, well monitors, etc., which have provided valuable field experience for the development of the MAR projects.

6.3.8. The "space for collaboration" in socio-technical systems

The combination of new hard structural measures, like managed aquifer recharge, and collective management institutions, like the CUAS, together make up a socio-technical complex system that follows a collaborative model.
This is a bottom-up, non-hierarchical network model of governance that - as will be presented below - is showing signs of being very effective in comparison to the usual top-down one, where water management decisions are, traditionally, imposed by Water Authorities.

This new organizational scheme (in Spain supported by Law) allows the inputs and contribution from single farmers and other agents to be submitted to the Board of the CUAS to be included in management decisions. Also, since these CUAS have been strongly supported from the onset by R&D projects, scientists can develop their research activities in association with these communities, with the added legitimacy of authorization by the Water Authorities.

This "space for collaboration" for the co-management of conjunctive use of groundwater resources that integrate MAR creates an "environment of trust" that improves the traditional (hierarchical) governance schemes, enhancing water security in relation to groundwater quantity. It is because of this higher level of internal coordination and collaboration with the river basin agency to protect over-exploited aquifers that specific actions could be taken, such as the installation and surveillance of flowmeters for effective control of groundwater abstractions. Regarding groundwater quality, the system is working better due to limitations in the application of agro-chemicals, especially fertilizers, through internal agreement in the CUAS under the internal supervision of the CUAS Board, which have become a locally recognized, accepted, and respected representative authority for each irrigation area.

The constitution of new CUAS depends on different environmental factors and the context of each community´s reality, which are quite heterogeneous, e.g., the groundwater body itself where CUAS are located. In the case of groundwater, especially in those cases where its constitution is compulsory, e.g. for water bodies at risk, the collective association occurs a posteriori. In this case, the initial reluctance is now changing for the individual holder, who feared that being forced to join a CUA would generate additional costs, offer less flexibility and independence, and thus overall more inconveniences with little perceived advantages. MAR initiatives have provided a natural and critical nexus between farmers to start to see the advantages of collaboration (internally) and coordination with the river basin agency (externally). MAR schemes guarantee a lower cost per user and increase the possibilities of using the water, allowing the rotation of plots, with potential cost savings. It also facilitates greater flexibility in the use of water and decision-making capacity for its members. Participation in the river basin agency´s formal bodies provides a better forum to negotiate issues, for example electricity tariffs or a simplification of paperwork.

Box 1: The Importance of Shared Data

The representatives of irrigation communities and CUAS provide data regarding the volumes used to irrigate each crop, the evolution of the groundwater level in their wells, the volume diverted from rivers (respecting essential environmental flows), volumes flowing along the MAR canals, infiltration ponds, and the reuse of reclaimed water from WWTPs) for MAR. In addition, datasets are captured by means of different sensors installed in different areas, guaranteeing a bilateral flow of information, providing a robust support of science-based figures and proven facts for, e.g., negotiations with the water authorities, which in turn help to improve the current legal and regulatory provisions.

The acquisition of local groundwater-related data greatly improves the quality of information and knowledge. Therefore, monitoring by the water authority, local irrigators and R&D projects is proving to be an important response measure, since datasets enhance the collective agreements and support proposals for water authorities and regulators within PPPP schemes. The term PPP in Spain refers to a collaboration to manage, in this case, water resources, between the government or public authorities and private landowners. Occasionally private landowners intervene to build infrastructure under this arrangement.

07

Conclusions, recommendations and next steps

Five decades of intensive groundwater exploitation have meant important economic, social, and environmental changes around the case study areas. From a hydrogeological perspective, wells had to be drilled deeper to reach groundwater. Extracted volumes from rivers have also increased and groundwater-dependent wetlands had disappeared, especially in the Medina area. The agricultural frontier was expanded and the conversion of dry land to irrigation areas had become the main means to increase farmers' income.

During this period, changes have also occurred in the legal framework and a space for collaboration was introduced which included the general population and end-users' participation in decision making. Nowadays, the result is that new communication channels have been set through the CUAS as a key stakeholder vis a vis the river basin agency, and also for stakehomers who are increasingly involved in the decision-making process regarding water security and governance.

Public-Private People Partnership (PPPP) and the combination of hard structural measures, soft non-structural techniques, and organizational negotiations have been the key elements in the creation of the "space for collaboration". The negotiations among the different actors have required new interactions and mediation. The "space for collaboration" offers an environment of trust with concrete and improved co-management results. Despite these new communication channels and collaborative spaces, some conflicts will still need to be resolved in the courts. The court makes explicit the conflicts of interest, existing tradeoffs, and the needed negotiations that are crucial for the development of the system, where ultimately all the actors work actively on a shared a vision for a better future of the area.

> *"Public-Private People Partnership (PPPP) and the combination of hard structural measures, soft non-structural techniques, and organizational negotiations have been the key elements in the creation of the "space for collaboration""*

As was analysed, the decline in groundwater level had a response from the public administration, initially proposed by end-users to implement MAR systems to address aquifer drawdown. The experience has had positive results overall, for example with job creation and economic growth due to improved yields and production. In addition, end-users have been able to save up to 36% in energy consumption thanks to the increase in groundwater table levels. MAR is also reducing agricultural depopulation. From the experience gained, MAR has become a key element for agricultural development and water security.

The firm commitment to MAR in this region to help counteract the impact on groundwater caused by irrigation has given these organizational systems an extremely high level of importance for internal management and to influence the legal measures and governance rules. It is an example of PPP as collaboration for the management of a resource among public authorities and private landowners.

However, after the physical observations on drawdown, yields, and the results gathered in interviews and workshops, some pending issues remain. Despite the good results provided by MAR and co-MAR, the extraction of groundwater is still very intensive with an exploitation index greater than one. New aquifer recharge experiences could be conducted in Los Arenales and Medina areas to bring this index down. A prospective basin study of potential MAR sites and techniques has already been done (Tragsatec-CHD, 2010), and the new river basin plan should incorporate "MAR guidelines". Nevertheless, this needs to be complemented by demand management and a strong oversight over water extractions so the recharge does not benefit "free-riders" who are not part of the formal MAR arrangement and that could benefit from a program without paying their fair share. Respect for the agreed rules is critical for long term collaboration and collective action.

A "shift in paradigm" is necessary in the water sector, from traditional patterns of water consumption and top-down decision making to evolve to a circular economy approach in which wastewater resources are not considered a waste, but rather an important asset in a context of water scarcity, especially in over-exploited aquifers. In these circumstances, MAR gains even more importance when complementing other measures. A change in the current regulation regarding water quality desired for reuse would be important to achieve this target. The strongly regulated modernization of the irrigation systems and the adoption of measures to improve water and energy efficiency are key elements to reduce over-exploitation impacts, provided this are backed by strong natural resource accounting and sustainable limits, leading to better economic results from costs and resource savings.

However, in line with the sociotechnical lens adopted here, technology is only part of the solution. Apart from technical advances, changes to the current organizational structures are essential to incorporate more intense and deeper end-user and public participation. The impact of the different dissemination and technology transfer activities is becoming central to increase users' capacity. The stakeholders' participation becomes even more effective when stakeholders come with experience, knowledge, and training. The communication between authorities and end-users also becomes both more fruitful and pragmatic. Some good educational and dissemination activities have been possible thanks to the good relationship between technicians and end-users, with a direct effect on agricultural development. The challenge in the future is to ensure singular cases of success can become more generalized and become good examples to replicate.

In short, the advantages of the space for collaboration helps to build the trust needed to overcome the disadvantages, with a positive balance, where all the actors play an important role in this new governance for future water security. Some newer mechanisms should be discussed regarding the space of collaboration concept, as identified in the following recommendations.

Deepening the Space for collaboration

Some key actions regarding groundwater stewardship have been undertaken by the river basin agency as the primary stakeholders. The most important ones are
i) the categorization of poor status for these groundwater bodies on account of their Water Exploitation Index and pollution levels; ii) the implementation of measures to control groundwater extraction by means of flowmeters, remote sensing monitoring of compliance with exploitation plans agreed with users, and iii) the authorities´ sovereignty to declare water bodies “at risk”. The “space for collaboration” and the progressive creation of an “environment of trust” have become important elements for better decision making.

Recommendation*: it is critical that these elements of oversight and strong collaboration are strengthened and deepened, creating venues for fluent communication with users involving all actors on future decisions on the management of the system, particularly water rights, monitoring and evaluation.*

MAR with added post treatment processes for better water quality

The alleviation of aquifer over-exploitation in these water bodies has benefitted from MAR. Results indicate that under MAR, the number of hectares under irrigation has increased, while the water level has recovered slightly, demonstrating it is a useful technique to address aquifer overexploitation. Other technical measures could also help, like wastewater treatment plants to provide MAR with a better water quality, possibly complemented by post-treatment processes.

Recommendations*: develop schemes that increase the self-purification capacity of the system and biofilter effectiveness, e.g. artificial wetlands and infiltration ponds equipped with reactive layers of interactive filters.*

Decision support systems that combine the technical and the social aspects

Some of the barriers discussed earlier indicate that it would be important to develop a legal definition of the “space for collaboration” under MAR. Experience with the MAR actions so far shows that improved control and surveillance operations have been particularly important. DSS and MAR have been intrinsically interconnected through both hard and soft aspects, including: the selection of “MAR zones” (areas where this technique is applicable); changes in the regulations according to changes in environmental conditions; changes in water management parameters at multiple scales; and organizational changes. The evolution of the systems themselves has caused the permanent design and/or adoption of DSSs as a mechanism of adaptation to the new changing circumstances and, of course, gaining experience to deploy future DSS on other over-exploited aquifers.

Recommendation*: study the economic aspects to avoid potential conflicts of interest in ranking the different uses of water, as well as the selection of MAR zones and their prioritization.*

Acknowledgements

The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under The Marie Skłodowska-Curie Grant Agreement no. 814066 (Managed Aquifer Recharge Solutions Training Network – MARSoluT) (https://www.marsolut-itn.eu/), the European Union project MARSOL (www.marsol.eu) GA nº. 619120 and the H2020 project NAture Insurance value: Assessment and Demonstration (NAIAD) GA nº No 730497 (http://naiad2020.eu/).

The authors are grateful to all scientists and practitioners who contributed to see this publication published.

Finally, we want to express our sincere gratitude to the anonymous reviewers for their valuable suggestions.

References

Ansell, Chris. & Alison, Gash. (2008). *Collaborative Governance in Theory and Practice. Journal of Public Administration Research and Theory*, 18(4), pp. 543-571. (PDF).

CHD. (2016). Duero River Water Basin Plan (PHD). Spanish Official Bulletin BOE 16, 2016 Jan 19th, pp. 3371-3372.

Custodio, E. (2002). Aquifer overexploitation: what does it mean? *Hydrogeology Journal (2002)*, 10, pp. 254-277.

DINA-MAR. (2011). Multiauthor. Management of artificial recharge of aquifers in the framework of sustainable development (Coord. Enrique Fernández-Escalante) 496 pg. Ed. Tragsa Group. ISBN 978-84-614-5123-4.

FAO-UNESCO. (2003). Education for the agricultural population. The role of education, training and capacity building for poverty reduction and food security.

Fernández-Escalante, E. (2005). Artificial recharge of aquifers in river basins. Qualitative and environmental aspects. Technical criteria obtained from the experience in the Cubeta de Santiuste, Segovia. Thesis. Univ. Complutense de Madrid. 1.346 pg. http://eprints.ucm.es/7154/.

Fernández-Escalante, E. & San Sebastián, J. (2017). Managing aquifer recharge: a focus on Latin America, chapter 22: Managed recharge in the Los Arenales aquifer, Castile and Leon, Spain. Technological solutions applied to agricultural development. IMTA, Mexico.

GWP. (2000). Integrated Water Resources Management, TAC Background Paper no. 4 GWP (2000): Integrated Water Resources Management, TAC Background Paper no. 4).

Hodge, G. A. & Greve, C. (2007). Public–Private Partnerships: An International Performance Review. *Public Administration Review,* 67(3), pp. 545–558.

INE. (2014). Spanish National Institute of Statistics. Statistical Yearbook.

López-Gunn, E. & Rica, M. (coords.) (2013). Multiauthor. Collective management of groundwater in Spain. F.M. Botín.

MARSOL: Fernández Escalante, E., Calero Gil, R., González Herrarte, B., San Sebastián Sauto, J. & Del Pozo Campos, E. (2015a). "Los Arenales demonstration site characterization. Report on the Los Arenales pilot site improvements". MARSOL deliverable 5-1, 2015-03-31. MARSOL-EC.

MARSOL: Fernández Escalante, E., Calero Gil, R., Villanueva Lago, M. & San Sebastián Sauto, J. (2015b). "Problems and solutions found at "Los Arenales" demonstration site". Del. 5-2, 2015.11.30.

MARSOL: Fernández Escalante, E., Calero Gil, R., Villanueva Lago, M., San Sebastián Sauto, J., Martínez Tejero, O. & Valiente Blázquez, J. A. (2016a). Appropriate MAR methodology and tested know-how for the general agricultural development. Del. 5-3, 2016-07-31. MARSOL. http://www.marsol.eu/35-0-Results.html.

MARSOL: Fernández Escalante, E., Calero Gil, R., Villanueva Lago, M. & San Sebastián Sauto, J. (2016b). Managed Aquifer Recharge to Combat Groundwater Overexploitation at Los Arenales Site, Castilla y León, Spain. Del. 5-4.

Mayor, B., Marcos, C., de la Hera, A., López Gunn, E. *et al*. (2020). Del. 6.4: Potential for adopting insurance value in risk management strategies. Paper 10: Medina. EU Horizon 2020 NAIAD Project, Grant Agreement N° 730497.

Rodríguez-Estrella, T. (2012). The problems of overexploitation of aquifers in semi-arid areas. HESSD 9, pp. 5729–5756.

San-Sebastián-Sauto, J., Fernández-Escalante, E., Calero-Gil, R., Carvalho, T. & Rodríguez-Escales, P. (2018). Characterization and benchmarking of seven managed aquifer recharge systems in south-western Europe. *Sustainable Water Resources Management*, 4, pp. 193–215. https://doi.org/10.1007/s40899-018-0232-x.

Tragsatec-CHD. (2010). Proposal of viable areas for artificial recharge with surface and sub-surface devices. JCyL.

UN Water. (2013). Water Security & the Global Water Agenda. A UN-Water Analytical Brief. ISBN 978-92-808-60382.

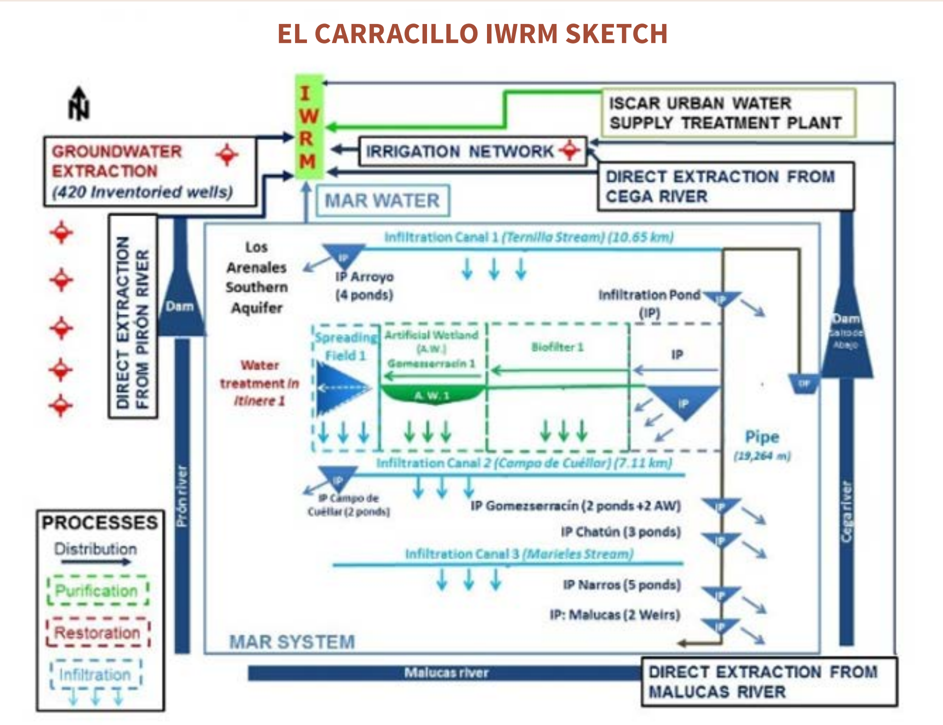
UNESCO. (2020). Multiauthor. Exemplary case studies of sustainable and economic managed aquifer recharge (in press). El Carracillo Managed Aquifer Recharge for Rural Development in Castile and Leon, Spain. https://bit.ly/2SMMPo6 https://bit.ly/3nz7qdH

Annex 1: Detailed Description Of Case Study Area

MAR CASE STUDY 1: El Carracillo scheme

The system integrates a fish-bone pipeline network as a 19.2 km aqueduct from the Cega river (Salto de Abajo site) to 14 distribution points, either in infiltration ponds or to the heads of MAR canals. Several MAR techniques are used, including 16 infiltration ponds, 17 km of MAR canals, 2 spreading basins and 3 artificial wetlands. The scheme includes reused abandoned wells and sand pits.

The water allocation is controversial. The maximum flow to be diverted is 1,370 L/s from January 1st to April 30th, and an environmental 6,898 L/s minimum flow rate must be respected (initial permission), measured in the river´s flow-meter next to the Salto de Abajo site. The total volume must be less than 22.4 Mm3/year. The percentage of water diverted from the Cega River with respect to the total flowrate has been about 16% as an average during the winter and spring (rainy seasons) periods since the MAR activity began. The total number of days that water was withdrawn during the allowed period (winter and spring) is about 62% of the whole potential. This permission has been challenged by environmental groups, because they consider the extraction from the river to be excessive. The final resolution will be decided by a court decision shortly. The Figures below include: (a) the topologic scheme, exposing the whole water management components in the MAR system; and, (b) the volume of water infiltrated for each MAR cycle since the activity began.



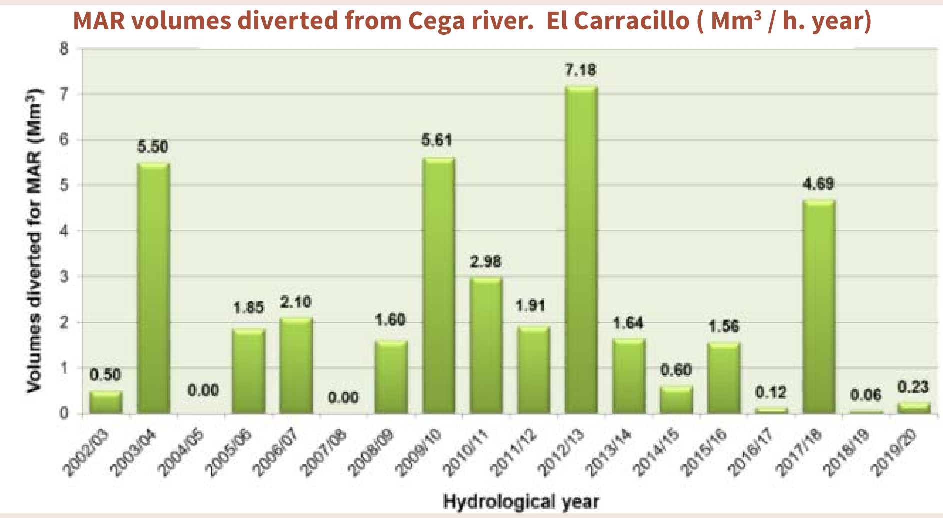


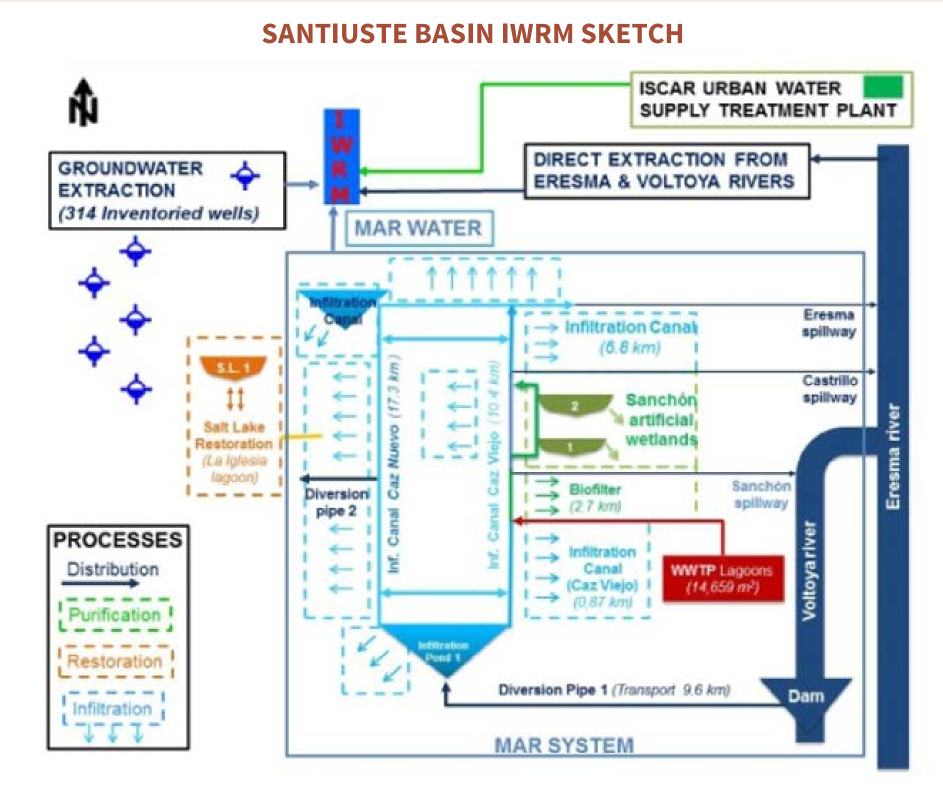
Figure 1-12 *El Carracillo IWRM scheme (a) and contribution of MAR to the water balance (2003-2020) (b)*

MAR CASE STUDY: Cubeta de Santiuste de San Juan Bautista scheme

The components of the MAR system are about 27 km of MAR canals, five infiltration ponds, three artificial wetlands, an inverse riverbank filtration (RBF) system and three high diameter infiltration wells.

Figure 1-13 includes: (a) the topologic scheme depicting the water management components in the MAR system; and, (b) the volume of water infiltrated for each MAR cycle since the activity began in 2002.

According to the permit C-21766-SG (MC/C-961/2013-SG) the water is diverted from the Voltoya River (DU-827) at the point called "Azud de los Navares", from December 1st to May 31th, as long as the river maintains an environmental flow of over 1,000 l/s at the Coca gauge station. The percentage of water diverted with respect to the total flowrate has been about 40%, as an average, during the winter and spring when most of the rain occurs in this climate. The total number of days, as a percentage of the maximum possible allowed, is about 47%.



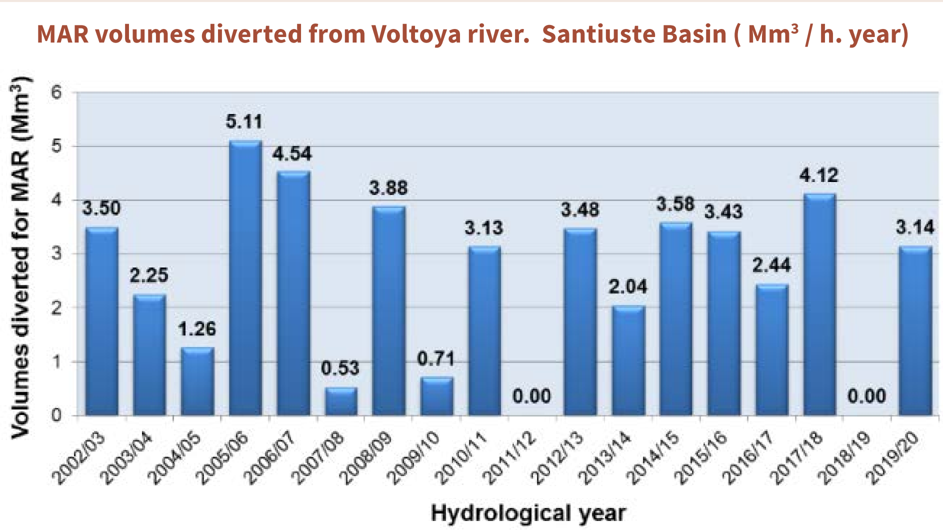


Figure 1-13 Cubeta de Santiuste de San Juan Bautista IWRM scheme (a) and contribution of MAR to the water balance (2002-2020) (b)

MAR CASE STUDY 3: Pedrajas-Alcazarén scheme

The Pedrajas-Alcazarén MAR system is novel with respect to previous experiences in the water intake diversification, originating from 3 different sources: a river diversion from Pirón River, a WWTP with advanced secondary treatment and a ditch to convey runoff from the village roof tops to a connection point where the MAR canal starts. This complex design, based on the variation of water sources, secures the continuity of the system in which water does not exclusively rely on winter surpluses and legal concessions on river diversions for MAR. The diversity of origin for the water is a key issue to assure the technical success of the integrated scheme.

The components of the system are the SAT-MAR or combination of a WWTP and a MAR system, a 2 km long pipeline, 5.5 km of infiltration canals, an RBF system and two infiltration ponds situated in the previous locations of sand quarries.

The Figure below includes the topologic scheme (a) and the volumes infiltrated from the SAT-MAR system since 2011 (b). It is unique, with full continuity secured because water for infiltration proceeds from a WWTP with "advanced secondary" treatment. The permit to operate the MAR system does not regulate the outflows from the WWTP and the runoff canal. The diversion from the river Pirón has been challenged by other users and is currently pending resolution through the courts. Regarding the technical approach, some specific MAR solutions have been applied and tested, most of them applicable in alternative scenarios. The key elements developed have been: (1) the diversification of sources at Los Arenales to increase the security of water supply (river diversion, runoff, WWTP outputs); (2) water security based on advanced monitoring for both quantity and quality over specific designed networks; and (3) impact assessment and study of the evolution of the indicators, including those targeting achievement of water project objectives.

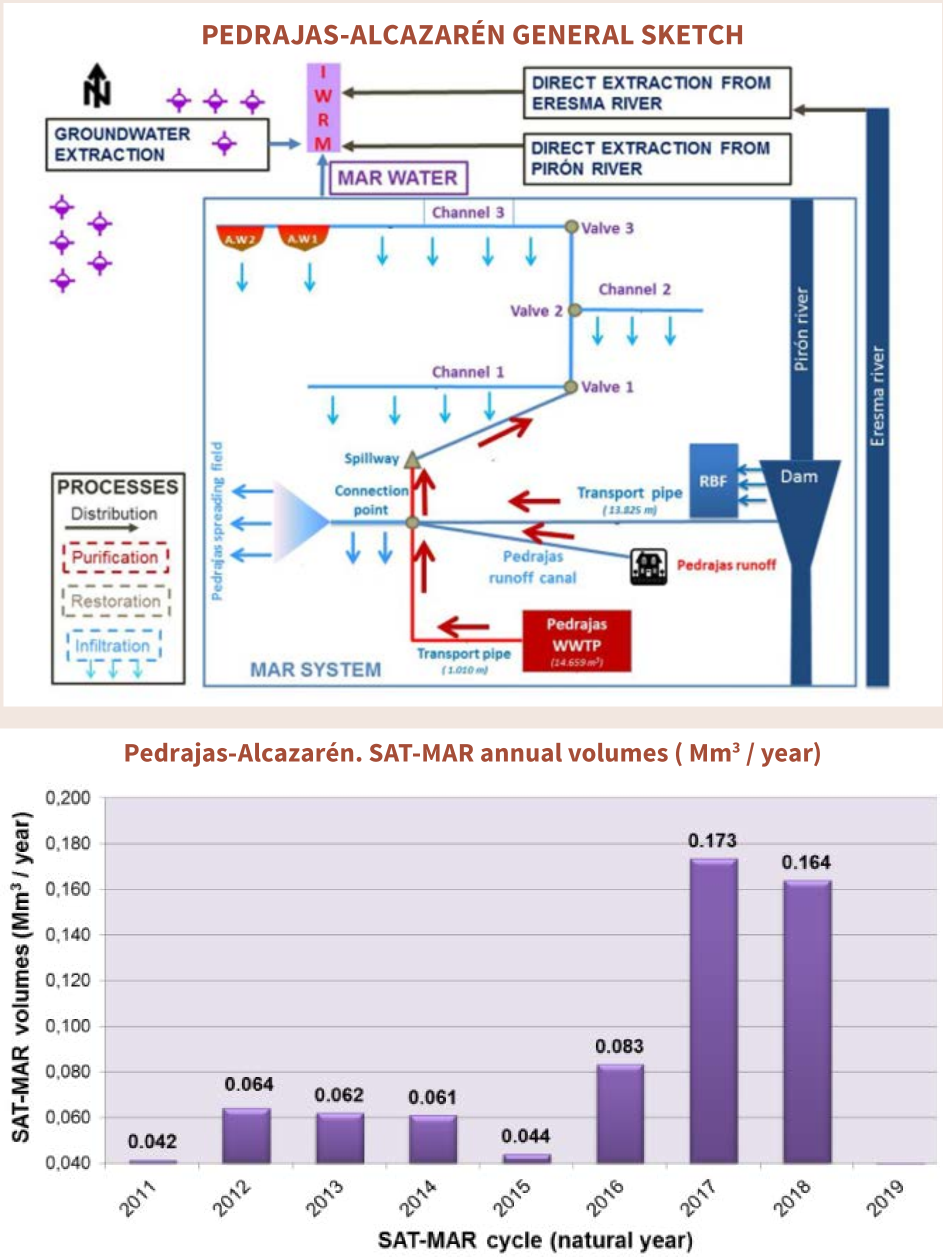


Figure 1-14 Alcazarén IWRM scheme (a) and contribution of the SAT-MAR to the water balance (2011-2020) (b)

2

Drivers for Collective Groundwater Management: The Case of Copiapó, Chile

Elisa Blanco and Guillermo Donoso

Elisa Blanco, Departamento de Economía Agraria, Pontificia Universidad Católica de Chile, Santiago, Chile.
e-mail: emblanco@uc.cl
Guillermo Donoso, Centro de Derecho y Gestión de Aguas and Departamento de Economía Agraria, Pontificia Universidad Católica de Chile, Santiago, Chile.
e-mail: gdonosoh@uc.cl

Abstract

Collective action has had positive results for surface water management. However, the scenario has been less explored when it comes to groundwater. This study analyzes an exemplar case regarding collective groundwater management in northern Chile. Its purpose is to analyze the barriers that limited or delayed the formation of collective action, as well as the solutions that afterwards lead to a fully organized groundwater organization. This focus highlights how to establish multi-stakeholder communities in places with extreme water depletion and water conflict. The approach adopted as a methodology involves the analysis of a case study through the application of the Design Principles for Sustainable Management of Common-Pool Resources and the Social-Ecological Systems (SES) framework.
All of the above help explore the institutional structures that support arrangements to manage common resources in a sustainable way.
The Copiapó basin is located in a highly productive area, with a situation of extreme over-extraction and is characterized by serious water conflicts. Despite the above, the basin is currently fully organized into groundwater users' communities with representative boards. To achieve this, a number of barriers had to be solved regarding information, trust issues, and a bureaucratic institutional system. An external technical team used innovative strategies to establish formal groundwater user associations, considering their legal documents, a consensual users registry, and finally, a monitoring system for wells. The analysis shows the relevance of three elements for the development of self-groundwater governance: the existence of a neutral and technical team that acted as mediators;
the identification and empowerment of leaders; and the limitation of the administrative authority in the community's decisions.

Keywords

Groundwater communities, groundwater governance, integrated water management, collective action

01

Introduction and a Brief Context

Conflict is part of the dynamics of any socio-economic and ecological system that involves multiple stakeholders with varying agendas, understanding, and perceptions. These social systems are typical of common resources, with various decision centers, each with limited and autonomous decisions, all operating under delimited set of rules (Ostrom, 1991). There are usually a multiplicity of institutions participating simultaneously, in a rather complex and messy structure.

In water matters, the systems are even more complex, given the wide variety of geo-climatic diversities of each area; cultural, historical, and institutional divergencies, as well as having a wider range of purposes for water use. Groundwater resources provide a whole new level of complexity. Since they cannot be seen and are expensive to monitor; a major concern is the general lack of information about groundwater and insufficient knowledge about its dynamics. Most aquifers have gaps in terms of data and models on the interaction of ground and surface waters, seawater intrusion, and groundwater quality levels (Donoso *et al*., 2020; Gorelick & Zheng, 2015; Kinzelbach *et al*., 2003). This is particularly worrying when facing higher levels of uncertainty in groundwater recharge, posed by climate change, and increased demands for water use due to economic development.

"Groundwater resources provide a whole new level of complexity since they cannot be seen and are expensive to monitor"

As for many countries, the Chilean legislation regarding water resources has focused on solving surface water management issues, almost forgetting about groundwater particularities. Here, the government - i.e., the public sector - grants water rights depending on the water available, and the private sector is in charge of its management through the organization of local water users. There are different instances of conflict resolution, but the local community is the first to intervene in resolving them. The non-recognition of groundwater in their initial legal documents has had a diverse range of effects. This non-recognition led to an over-use of aquifers and reservoirs, as well as the increase of several conflicting situations. It also led to the fact that ground and surface waters are managed independent of each other, and the effects on the recharge of aquifers due to the modernization of irrigation are not being considered nor analyzed (Donoso *et al*., 2020). This regulatory absence has been covered with groundwater guidelines established by the public water authority, the Dirección General de Aguas (DGA), through internal administrative acts (Rivera, 2015). While this trend has experienced some variations in recent years, the precariousness of the treatment of groundwater remains and the current Chilean water legislation contains insufficient rules to effectively regulate groundwater resources (Rivera, 2015; 2018). This void regarding groundwater has not impeded the emergence of collective action.

This is the case of Copiapó valley in the dry northern Chilean region, where users adapted themselves to the current institutional and normative system and were able to organize the first groundwater user communities in the country. Twenty years ago, the basin used to be highly conflictive among the different water users, namely mining, agriculture, and urban. The situation led to extreme over-extraction, where not only did the river disappear, but the aquifer started dropping its water level fast (Donoso *et al*., 2020). In 2004 the first self-managed groundwater user association in Chile was legally formed in the lower part of the basin and, later on, four others followed its steps. Currently the basin is fully organized into groundwater users' communities with representative boards, partially nested in the surface water association and most wells now have monitoring devices. With these institutional, managerial, and technological improvements, the aquifer is now completely self-managed by users.

The main objective of this article is to analyze the barriers that limited or delayed the formation of Copiapó's groundwater associations, as well as the triggers/solutions that afterwards lead to their formal establishment. This case study sheds light on how to: enhance the development of self-managed groundwater users' communities; establish multi-stakeholder participation and negotiations in places with extreme depletion and water conflict; and derive lessons for policy makers on the development of groundwater management and governance.

02

Methodology and Conceptual Framework

The study of the Copiapó basin was done by combining empirical work - improved with a literature review - and the application of the Design Principles for Sustainable Management of Common-Pool Resources and the Social-Ecological Systems (SES) framework.

Groundwork to directly assess the formation and empower groundwater communities in Copiapó was conducted between the year 2012 and 2015. The work involved different instances of participation with local water users. Among others, the tasks carried out included:

- Monthly field campaigns for the identification of users, potential directives, and finally, the formation of four new groundwater communities in the valley (communities from sub-aquifers 1 to 4). With them, it was possible to develop a model of statutes to be used by the four communities.
- With the existing groundwater community, the team worked directly with the Community Administration and with its Board of Directors, on the proposals for the normative documents. Also, monthly meetings were held for accomplishing this aspect. It involved the modification of their current statutes as well as the development of internal operational regulations and procedures manual.
- Running a training course for community members, where the topics to be addressed were defined collectively. Each training was carried out for the whole community, and in greater detail, for the Board of Directors. A total of fourteen training instances were carried out for users, focused on water terminology, hydrology of the valley, current situation of the resource in the area and the main duties and attributions that involve taking part of a groundwater community.
- Also, six workshops were carried out to discuss the use of public funding for implementing better irrigation technologies at farms, as well as a monitoring system for the communities.
- The team also supported the communities by georeferencing all wells. The work began in sectors 5 and 6 (located in the lower part) of the Copiapó valley, and then began gradually completing the georeferencing of the upper zone, accounting for 100% of the existing wells.
- Finally, two massive seminars were held, open to the whole community, to inform the public about the project, the objectives, the achievements and their importance for the valley.

To support the analysis, a literature review was also carried out, regarding scientific articles and project reports of studies regarding water governance that were conducted in the area.

Finally, to guide the diagnosis and analysis, tools from Design Principles for Sustainable Management of Common-Pool Resources, and the Social-Ecological Systems (SES) framework were used. These tools allow us to explore the institutional structures that support arrangements to manage common resources in a sustainable way. A brief summary of these frameworks is provided below.

2.1. Design Principles for Sustainable Management of Common-Pool Resources

In 1968, Hardin published his well-known Tragedy of the Common Goods theory, stating that individuals sharing a common resource will act for their own benefit, obtaining worse results than if they acted collaboratively (Hardin, 1968). However, Ostrom (1990; 2000; 2015a) observed that the Tragedy and the self-interested attitudes were preventable. She studied several cases where voluntary organizations using collective action were able to manage their resources sustainably. For this to happen, eight design principles were defined as key for successfully governing the commons. These are: 1) the definition of clear boundaries; 2) that rules are aligned with local needs and that 3) these can be modified by participants; 4) respect from external authorities; 5) the development of a system for monitoring compliance; 6) gradual sanctions; 7) accessible and low-cost solutions to disputes; 8) enforced through multiple layers of "nested" organizations (Ostrom, 2015a).

Later, these design principles were reviewed and expanded, while being contrasted with a greater number of case studies (Cox *et al*., 2010; 2016). For example, the first principle expanded into 1A) Individuals or households who have rights to withdraw resource units from the common-pool resource (CPR) must be clearly defined; and 1B) The boundaries of the CPR must be well defined (Cox *et al*., 2010). Thus, for successful collective governance to happen, regarding any common resource, these principles should be present.

These design principles as analytical tools have been widely used in water management and irrigation, including interstate or transnational river basins (Heikkila *et al*., 2011). Even in Chile, the tools have been used to analyze water users associations as a whole (Donoso, 2018), or case studies from specific basins (Rinaudo & Donoso, 2019). Therefore, these principles are useful for establishing a diagnosis of the Copiapó case study, since they can extend their use towards water resources, and even for groundwater. They can help identify aspects that can allow or impede an effective groundwater collective governance.

2.2. Social-Ecological Systems (SES) Framework

Together with the Design Principles, the Institutional Analysis and Development (IAD) framework was conceived (Kiser & Ostrom, 1982). The goal of the framework was to understand the ways in which institutions operate and change over time, with focus on communities without state intervention and their governance over common pool resources (McGinnis, 2011). At the IAD's core is the 'action arena', composed of an action situation and actors. The first refers to a social space where the actors interact, solve the commons problem, and exchange goods and services, while the actors are those who participate in the situation (Ostrom, 2007; Ostrom *et al.*, 2007).

IAD involves the analysis of the interactions and outcomes of this 'action arena' regarding evaluation criteria, as well as exogenous variables that change the analysis of the case study as they vary (Ostrom, 2011). Regarding water, Ebenhöh (2007) adapted the framework to generate an agent-based model for water management regimes, and Zhang (2018; 2019; 2020) has used the framework to analyze different water regimes in China. In all of the above, the convenience of using the framework to analyze water systems was proven.

Table 2-1 Variables of analysis for the Social-Ecological Systems (SES) framework (Source adapted from Ostrom, 2007)

Social, Economic, and Political Settings (S)	
S1- Economic development	S4- Government water policies and commitment
S2- Demographic trends (density, settlement pattern)	S5- Market incentives (distance to market)
S3- Political stability	S6- Media organization

Resource system (RS)	**Resource Units (RU)**	**Users (U)**	**Governance System (GS)**
RS1- Sector	RU1- Resource unit mobility	U1- Number of users	GS1- Government organizations
RS2- Clarity boundaries	RU2- Growth or replacement rate	U2- Socioeconomic attributes of users	GS2- Non-government organizations
RS3- Size of resource system	RU3- Interaction among resource units	U3- History of use	GS3- Network structure
RS4- Human-constructed facilities	RU4- Economic value	U4- Location	GS4- Property-rights
RS5- Productivity of system	RU5- Size	U5- Leadership	GS5- Operational rules
RS6- Equilibrium properties	RU6- Markings	U6- Norms/social capital	GS6- Collective rules
RS7- Predictability of system dynamics	RU7- Spatial & temporal distribution	U7- Knowledge of SES models	GS7- Constitutional rules
RS8- Storage characteristics		U8- Dependence on resource	GS8- Monitoring & sanctioning processes
RS9- Location		U9- Technology used	

Interactions (I)	**Outcomes (O)**
I1- Harvesting levels of diverse users	O1- Social performance measures
I2- Information sharing among users	O2- Ecological performance measures
I3- Deliberation processes	O3- Externalities to other SESs
I4- Conflicts among users	
I5- Investment activities	
I6- Lobbying activities	

Related Ecosystems (ECO)	
ECO1- Climate patterns	ECO3- Flows into and out of focal SES
ECO2- Pollution patterns	

In the past decade, the Social-Ecological Systems (SES) Framework was developed as an ongoing effort to revise the IAD framework. This was done in order to give equal attention to the biophysical and ecological foundations of institutional systems. The idea was to analyze patterns of interactions (I) and outcomes (O) imbedded in the SES, called the Focal Action Situation (McGinnis, 2011). The framework assists organizing relevant variables regarding specific attributes of i) the resource system (RS), ii) the resource units (RU) generated by that system, iii) the users (U) of that system, and iv) the governance system (GS) (Ostrom, 2007). The analysis could also include aspects regarding v) social, economic and political settings (S), to incorporate the broader context within which the governance system per se is located, and vi) related ecosystems (ECO) to include a broader ecological context (see Table 2-1).

The latter has been applied to a variety of studies regarding the institutional scope of SES, such as forests, fisheries and water resources. Regarding water institutions, Meinzen-Dick (2007) proposes hypothetical factors that could influence interactions and outcomes regarding irrigation systems. Rather than setting up rigid institutional models, the overall notion of the framework is to recognize the differences among sites and make specific provisions for each case analyzed (Ostrom, 2007). Since the institutional settings are then adjusted to specific requirements, this approach avoids carrying out large or costly investments with no long-term improvements, or without generating dependencies on external help (Lam & Ostrom, 2010; Ostrom *et al.*, 2011).

The framework has only been applied for irrigation and does not consider a deeper analysis of the interactions of users with different purposes. It has not been applied considering different administrative units, such as the analysis of a community, micro-basin, a complete basin, or even the institutional framework of a country or transboundary agreement. A step towards this type of multi-level institutional analysis was carried out by Oakerson and Parks (2011), nevertheless it was limited with respect to protected areas. Thus, the framework can be extended to be used in the analysis of groundwater socio-ecological system, such as the Copiapó case. It can be especially helpful for identifying problems, barriers, and triggers for successful cooperation, and can help detect elements to achieve water security at a basin level.

“The framework can be especially helpful for identifying problems, barriers, and triggers for successful cooperation, and can help detect elements to achieve water security at a basin level”

03

Copiapó Case Study: Context, Problems and Barriers to Their Resolution

3.1. Context

The Copiapó basin is located in northern Chile, an extremely dry area. Copiapó only has about 28 mm of rain a year (DICTUC, 2010). At the same time, this is a highly productive area in terms of mining and agriculture. Both activities depend considerably on the existing water resources in the basin, which means that water stress can affect the entire economy of the area. At the same time, water is needed for the cities of Copiapó and Tierra Amarilla, environmental preservation of wetlands, and for the cultural well-being of indigenous communities (DGA, 2004). Thus, there is a high and diverse demand for water in the area that contrasts with the low precipitation received annually in the valley. At present, agricultural water use accounts for 75% of groundwater withdrawals, while mining and industrial activities account for 15%, and drinking water supply, 10% (PUC, 2014).

The Copiapó aquifer was divided into six administrative sectors[1] from the Andes Mountains until it joins the sea (Figure 2-1). The melting snow and ice from the mountains is the main contribution to the recharge of the basin, reaching its maximum in the summer months (McFarlane & Norgate, 2012). Surface water is extracted mainly in the upper part of the basin since the river has stopped flowing superficially downstream and groundwater is the only water source in these lower areas. At present, the estimated recharge of the basin equals approximately 3,700 L/s. However, water rights have been granted for a total of nearly 19,600 L/s, more than 5 times its capacity. Even though a significant part of the allocation belongs to farmers, who do not use these resources all year long, the aquifer is still under an extreme overallocation of water rights. As expected, groundwater levels started dropping. A study carried out in 1994 already pinpointed a negative balance between the water that was entering and that being extracted from the basin in the area of the city of Copiapó (DICTUC, 2010). This situation has only worsened since.

The river is managed by a Vigilance Committee, a surface water users association. This collective organization is formed by the presidents of the boards of directives of all irrigation districts and other surface water communities.
In the year 2004, since the river did not flow in the lower sector of the basin, they did not consider themselves responsible to manage sectors 5 and 6. With the objective of developing water resources management and to achieve sustainable exploitation of the Copiapó river in these lower sectors, a groundwater user community was organized, the first community of its kind in Chile.

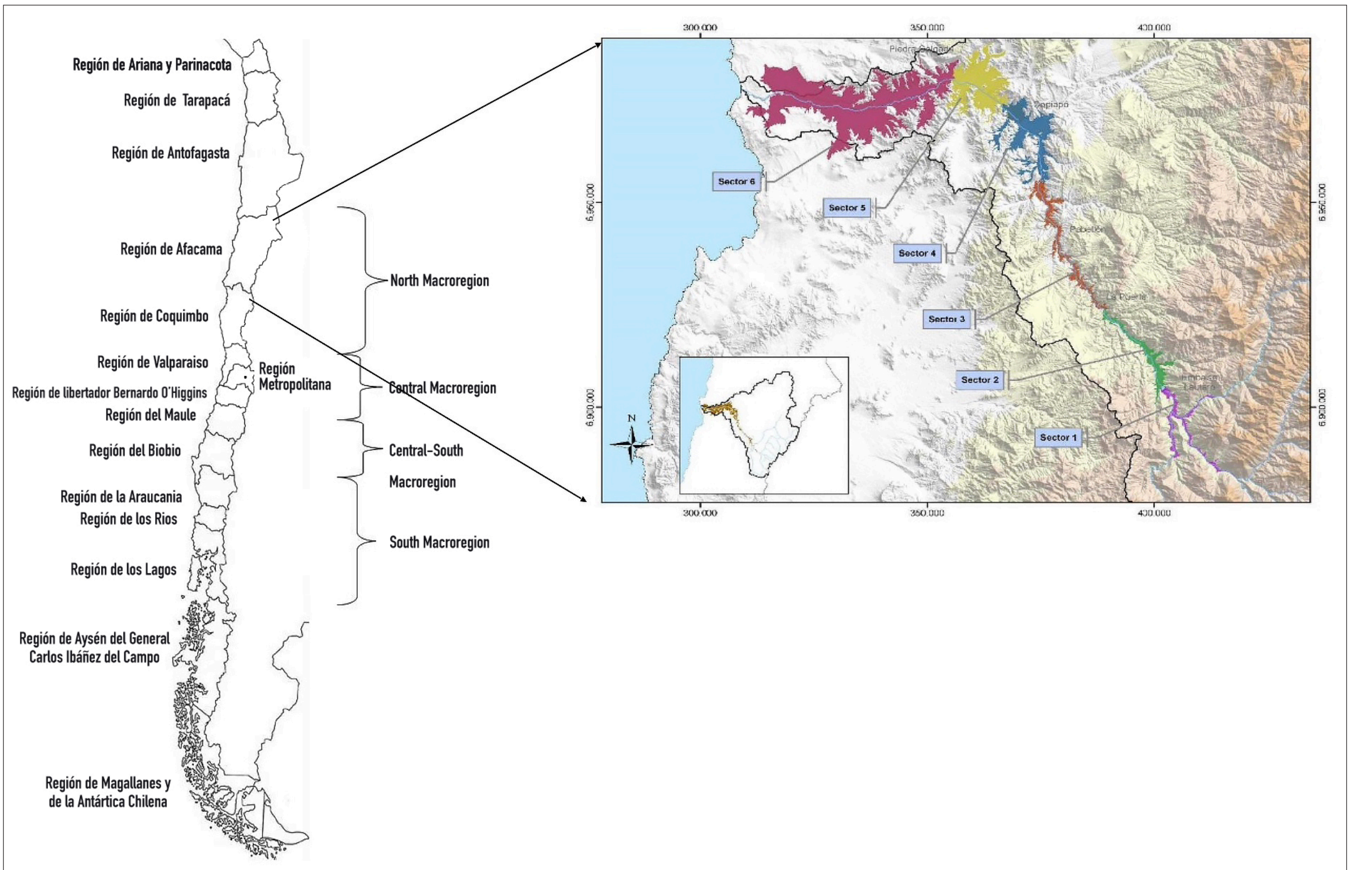


Figure 2-1 *Copiapó aquifer divided into six administrative sectors (Source adapted from DICTUC, 2010)*

Table 2-2 Groundwater communities in Copiapó analysis of degree of satisfaction of design principles for common resources governance (Source adapted and expanded from Rinaudo & Donoso, 2019, who analyzed only sectors 5 and 6)

	Principle (according to Cox et al., 2010)	Degree of satisfaction
1A	User boundaries: Clear boundaries between legitimate users and nonusers must be clearly defined	Satisfied. Users are defined by a system of well-established water rights, and the official registry is held by each groundwater community.
1B	Resource boundaries: Boundaries that define the resource system are present.	Satisfied. The aquifer and its boundaries have been clearly delineated.
2A	Congruence with local conditions: Appropriation and provision rules are congruent with local social and environmental conditions	Partially satisfied. The maximum water intake is defined by the system of water rights, and rules of operation are in place regarding monitoring, inspections and sanctions. However, since the groundwater levels are too low, these tools are used for an accountability process more than for a sanctioning one.
2B	Appropriation and provision: The benefits obtained by users from a common-pool resource, as determined by appropriation rules, are proportional to the amount of inputs required	Not satisfied. The initial allocation of the resource is given by the State. Even though a specific use has to be initially justified, it can be transferred to any other user. Thus, the water rights system in place is independent on how it is used.
3	Collective-choice arrangements: Most individuals affected by the operational rules can participate in modifying the operational rules	Partially satisfied. Their bylaws or statutes allow the participation of all users in the modification of their rules. However, since votes are proportional to the size of the water rights, small users feel excluded from the decision process.
4A	Monitoring users: There exists an accountable process of monitoring the appropriation and provision levels of the users.	Partially satisfied. Almost all wells are monitored, yet the communities do not have the technical resources to analyze and share the huge amount of data generated. This results in a lack of credibility.
4B	Monitoring the resource: Monitors who are accountable to the users monitor the condition of the resource	Partially satisfied. The hydrometric system in place is weak and can be noted by the contradictory results achieved by the different studies that have been conducted on the Copiapó aquifer.
5	Graduated sanctions: Appropriators who violate operational rules are likely to be assessed graduated sanctions (depending on the seriousness and the context of the offense).	Not satisfied. Even though the rules have been established, in practice, no significant sanction has ever been implemented, although there have been violations.
6	Conflict-resolution mechanisms: Appropriators and their officials have rapid access to low-cost local arenas to resolve conflicts among appropriators or between appropriators and officials	Partially satisfied. The boards of directors should arbitrate conflicts. Since the board is mainly composed of large or powerful users, their judgment is not perceived as impartial.
7	Minimal recognition of rights to organize: The right to devise their own institutions is not challenged by external governmental authorities	Satisfied. Almost all communities have been formally registered by the public authority, except for sector 1 (paused in the legal department review).
8	Nested enterprises: They are organized in multiple layers of nested enterprises	Partially satisfied. The groundwater communities have bought surface water rights to become a part of the surface Vigilance Committee.

Currently, five groundwater communities are in place: one for each groundwater aquifer sector, with the exception of sectors 5 and 6, that, as has been mentioned, are organized as one. Each one of them has a board of directors, with positions reserved for small farmers, medium farmers, large farmers, the mining sector and the sanitary/urban sector (PUC, 2014). They have hired a manager and have people surveilling the community's wells and the main basin storage infrastructure, the Lautaro Dam. Regarding water usage, almost all wells have monitoring devices that asses their water intake and satellite telemetry that sends the information to the community. Each organization has written bylaws where all their norms are established, including the definition and responsibilities of each member of the community, the number of directors, in what manner they will be assigned, in what way assemblies will be conducted, and how often will they be held, among others.[2] Also, they have rules of operation in place that provide details regarding the use of telemetry, possibility to enter private property to control pumping devices, and a system of sanctions (Donoso *et al.*, 2020; PUC, 2014; Rinaudo & Donoso, 2019).

In general terms, since the organization of the groundwater communities, the basin has advanced in several aspects regarding their self-governance. Considering the Design Principles for Sustainable Management of Common-Pool Resources, Copiapó's groundwater communities have their boundaries well defined and have achieved recognition from the public agency (see Table 2-2). They have made progress and achieve partial degrees of satisfaction on several other principles; however, they have not been able to truly adapt their rules to their local needs and do not have graduated sanctions.

3.2. Analysis of Obstacles to Sustainable Groundwater Management in the Copiapó Basin

Before the development of groundwater user communities, as Copiapó has today, the basin was struggling with different problems that had led to an extreme management crisis. When the basin was facing a severe drought, surface water users distributed their water rights proportionally, according to the water available, and their intakes continue to be monitored. This is managed by the surface Vigilance Committee at the river level, and, by law, they should be the ones in charge of the groundwater users as well (Rivera, 2018). However, in the Copiapó basin, this has not occurred.

Using the SES framework, we conducted a diagnosis on the basin situation before it was fully organized into groundwater communities; the results are summarized in Table 2-3. Looking at the Governance Systems (GS) variables analyzed, not only did the surface Vigilance Committee neglect the management of groundwater users, almost all governance elements analyzed failed as well. For example, even though there was a groundwater community in place, it did not develop operational rules, nor collective action norms, nor had the capacity to perform some monitoring or sanctioning processes. This led to a number of negative interactions or problems that could be seen as obstacles to groundwater governance.

The main identified problems are described in more detail in what follows.

Problem 1: Over-allocation of water rights. As has already been mentioned, the aquifer was being highly over-extracted, and its groundwater levels were quickly diminishing. In the past years, the aquifer level had started dropping and wells have had to be deepened as much as 200 m in order to get water in some areas (DICTUC, 2010). This generated a number of "hanging" wells, as well as an increase in electricity consumption, and an overall increase in costs to extract groundwater. This over-allocation was due to:

- The lack of studies that model and project the availability of water and contradictory reports on the effects of exploitation. In 1984, a study concluded that there are groundwater sectors where extraction equals recharge, so some aquifer sectors should close for new water withdrawals (IPLA, 1984). Contradicting such information, in 1993, was another model which estimated that the basin still had a margin for new abstractions, information that was refuted a year later (DGA, 1993; IPLA, 1994). However, in 1995, once again, a study stated that there was no overexploitation in the upper part of the basin (Álamos & Peralta, 1995). This assertion was supported by a study conducted in 2006 (Golder, 2006). Since then, all the studies carried out demonstrated the need for the closure of the basin due to problems of over-extraction (SITAC, 2008; DICTUC, 2010; McFarlane & Norgate, 2012; Fuster *et al.*, 2010).

- Lack of planning for the process of granting water rights. From all the studies mentioned earlier, only those done once the basin was closed considered climate change projections and interaction of surface and groundwater. They were not available during the years when most water rights were granted.[3]

- The use of the "foreseeable use factor" of water for the farming sector. The latter consists of estimating the number of permits that could be granted by taking into account only their intended use. Thus, the approach considers a theoretical use factor of water rights that assumed agriculture would consume 20% of its annual allotment and drinking water supplies and the mining industry would only consume 75% of their allotment (Rinaudo & Donoso, 2019). These assumptions were based on the seasonality and interannual variability of the extractions, as well as extraction efficiency. Due to improvements in water use efficiency, the actual use factor is much higher: closer to 40% for agriculture and 100% for mining and drinking water (Rinaudo & Donoso, 2019). Thus, the total volume actually extracted is much higher than the one estimated when the water rights were granted. The temporary introduction of

Table 2-3 Summary of variables analyzed in the Copiapó groundwater aquifer, using SES Framework

Social, Economic, and Political Settings (S)
S1- High economic development of the mining sector in the area already highly productive

Resource system (RS)	Resource Units (RU)	Users (U)	Governance System (GS)
RS1- Sector: Water RS2- Clear boundaries RS5- Significant scarcity RS6- Aquifer depleted and scarce hydrometric information	RU2- Seasonal water availability (mostly during spring) RU3- Hydrologic interaction between groundwater aquifers RU4- Costly agricultural and mining production	U1- Total number of wells in the basin was over 600. U2- High heterogeneity of economic sectors involved and wealth of users. U5- No clear leadership U6- No groundwater norms U9- Efficient irrigation technologies in place	GS1- A small public authority's office in place GS2- Only one groundwater community in place (sector 5 and 6) with limited capacity GS5- No operational rules GS6- No collective-choice rules GS8- No monitoring & sanctioning processes

Interactions (I)	Outcomes (O)
I1- Overallocation of water rights and maximum water usage by diverse users I4- Conflicts among users I6-1 Poor management capacity of communities in place I6-2 Surface Vigilance Committee not managing groundwater resources and each aquifer being managed as independent	O1- Lack of equity in water distribution (since big farmers and the mining sector have deeper wells, small farmers and rural communities are left with "hanging wells") O2- Aquifer depletion and salinity problems. O3- Higher energy demands (for deeper wells)

Related Ecosystems (ECO)
ECO1- Higher uncertainty of water availability ECO2- Appearance of pollution ECO3- Existence of wetlands at the beginning of the basin

the concept of foreseeable use value worsened the over-allocation situation (Jouravlev, 2005, Muñoz, 2010, World Bank, 2011).

These factors explain the overallocation: scarce and contradicting information; lack of planning; and the incorporation of the "foreseeable use factor", are shared in Rinaudo and Donoso (2019), as well as in Donoso, Lictevout and Rinaudo (2020). In both studies, the legal complexity of the Chilean system and political pressures, as well as compliance and enforcement problems -considering a lack of monitoring devices- also triggered an over-allocation of the resource.

Problem 2: Independent management of the underground connected aquifer sectors, and between surface and groundwater. The subdivision of the six administrative sectors, carried out after the study of Álamos and Peralta (1987), sought to achieve better administrative management of the resource (Golder, 2006; SITAC, 2008; DICTUC, 2010). However, in all technical studies, the interconnection between the different hydrogeological zones is acknowledged by recognizing that water intakes in the upper sectors of the aquifer affect the aquifer level in the sectors 'downstream' in the aquifer. In all studies, it is emphasized that the six sectors respond to an administrative rather than hydrogeological division. Nonetheless, because the aquifer was administratively sectorized, the public agency, the Dirección General de Aguas (DGA), has interpreted each sector as a hydrogeological division, thus endorsing the individual management of each sector (Donoso, 2014). Since the aquifer's water level has been dropping, salinity issues and increasing conflicts have ensued; having independent water management in these aquifers has proven to be suboptimal for the efficient water management of the basin as an integrated unit.

In the Copiapó river, although the Vigilance Committee, should exercise its actions towards surface and groundwater users,[4] it only actually manages surface water for irrigation districts and individual river intakes. Furthermore, since the river no longer flows downstream from the city of Copiapó, they justified their governance ending at the city, and not any further.

Other initiatives, such as the establishment in 2006 of a Public-Private Water Table to operate as a binding basin-level agency, and the establishment of a Regional Advisory Council for Water Resources[5] in 2014, have arisen (CSIRO, 2015). Nonetheless, they haven't worked or settled upon long-lasting agreements.

Problem 3: Poor or no groundwater management. In the lower basin, sectors 5 and 6, the first groundwater user community was organized, the Comunidad de Aguas Subterráneas (CASUB). Its main objective was to carry out groundwater management in its area of jurisdiction, which covers from the Copiapó city downstream to the ocean. This management includes seeking the sustainable exploitation of the resource, jointly managing quality and quantity issues, and ecosystem conservation. Even though the community was established in 2004, it only became active in 2008 and its management capacities have been limited due to the lack of rules of operation (Donoso *et al*., 2020).

Between 2012 and 2015, the authors of the present article conducted field work to strengthen CASUB. The diagnosis was that CASUB lacked the tools and resources to effectively manage the groundwater resource. The community was mainly focused on limiting the acquisition of new water rights, updating their user registry, as well as monitoring upper river flows and a small number of water wells. The situation was even more complicated upstream, since before 2012 there were no groundwater user communities established, nor any groundwater management controls.

Problem 4: Conflicts and trust issues between users. In Chile, water conflicts are a common issue regarding water management. A majority of these involve large companies, such as corporations operating large-scale mining projects, many of them located in the arid north (Bauer, 2015). According to Rivera, *et al*. (2016) the different conflicts arise as a result of the characteristics of the relationship between companies and communities. They highlight the lack of dialogue and agreements among the different sectors involved (Rivera *et al*., 2016). A subsequent study identified that, over time, conflicts have evolved to fewer topics that include the protection of property and the environment, and claims regarding the adaptation of water rights towards current legislation processes (Herrera *et al*., 2019). Although subjects tend to be recurrent, additional demands have been added in recent years, including technical components, and environmental and social issues (Rivera *et al*., 2020).

Copiapó is not the exception and is one of the provinces with the highest number of water disputes (Rivera *et al*., 2020). Besides having several legal water disputes, there is a high level of mistrust among water users in the basin. There are trust issues both among users themselves and with the authorities. An analysis carried out in the basin identified distrust of the mining sector, especially by farmers, a lack of credibility of public authorities, and mistrust of the drinking water providers (CSIRO, 2015).

The groundwater crisis that affected Copiapó was triggered by several problems, most of them regarding management issues. These problems are commonly found in other water basins, especially in those areas that depend significantly on groundwater reservoirs. In many cases, collective action has proven to be mutually beneficial for all parties (Lopez-Gunn, 2003; Lopez-Gunn & Martínez, 2006; Martínez & Hernández, 2003; Poteete *et al*., 2010). Thus, the question that arises is what acted as a barrier for users to organize themselves and develop successful groundwater self-governance.

3.3. Barriers for collective groundwater management

Even though collective management of these groundwater resources could help solve the problems identified previously, we identified specific barriers in the basin that acted as obstacles for the development of said strategy.

Barrier 1: Heterogeneity of the actors involved and no opportunities for conversation. There was difficulty in coordinating different requirements and needs of a diverse range of actors. In Copiapó, the existence of large, medium and small farmers, indigenous communities, mining companies, and the cities having different needs regarding the timing and quantity of the water required, affected their ability to coordinate, and thus, their ability to develop collective management. Multiple research support our finding, suggesting that different forms of group heterogeneity affect collective action (Poteete *et al*., 2010, Ruttan, 2006; 2008). On the matter, Tang (1991) shows that lower variance in the group income can be associated with a higher degree of rule conformance and good maintenance among irrigators. Along these lines, Wang and Segarra (2011) predicted that welfare losses arise in the presence of productivity heterogeneity. Using the SES framework, considering these aspects we conclude that the existence of different actors, in terms of income and production, was a barrier limiting their collective action.

Working with a range of stakeholders, all with different motivations, requires time, patience, and compromise (Powell & Bundhoo, 2019). In Copiapó, the lack of coordinated conversations, or a person/organization acting as a mediator, only worsened the situation. This conclusion is shared with Donoso, Lictevout and Rinaudo (2020), indicating that the absence of a forum where diverse stakeholders could gather to talk and debate about water issues is an important problem for the coordination throughout the basin. This is a regular problem in Chile related to groundwater issues (Abrigo, 2019; Rinaudo & Donoso, 2019).

Barrier 2: Disinformation regarding water available and granted water rights. The level of knowledge regarding granted groundwater rights, as well as the knowledge regarding the physical operation of the resource in Copiapó valley, truncated the emergence of collective management of the resource. First, there are significant gaps in the official water rights registry listed by the public authority, the DGA (Rinaudo & Donoso, 2019; World Bank, 2011; 2013). This is due to the fact that water rights given in the past have not all been adapted to the standards of the current legislation and customary water rights have not formalized their titles. Also, the DGA is not informed of water rights listed in real estate offices (Conservadores de Bienes Raíces), as well as several transactions between users. Thus, there was no agreement regarding who has water, when and where. To reduce this barrier, we built a water rights database using historic real estate registry information. This actualized water right registry was delivered to CASUB and became the basis to constitute the groundwater communities in the upper part of the basin

A second source of disinformation, as mentioned previously, is that even though several studies have been conducted on the Copiapó aquifer over the past few years, they have not shown agreement regarding the groundwater situation. This has been identified by several authors (Donoso *et al*., 2020; Rinaudo & Donoso, 2019; Troncoso *et al*., 2012). The disinformation regarding the list of users that should be considered in the water management, as well as the lack of information regarding water dynamics, is a critical issue for self-governing resources, as has been pointed out in numerous research papers (Meinzen-Dick, 2014; Ostrom, 2015b; Poteete *et al*., 2010; Powell & Bundhoo, 2019).

Barrier 3: Government bureaucracy problems. Copiapó's crisis and the lack of collective groundwater governance may also be explained as a consequence of severe governmental failure. Bureaucratic issues regarding a rigid public system can be pinpointed as problematic. As mentioned, despite the fact that the aquifer has proven to be connected in its six administrative sectors, and therefore joint management must be carried out, our proposal to develop a unique groundwater user community was rejected by the public authority, the DGA. Additionally, there was a significant delay in the resolution of regular procedures, poor digital documentation, and long delays due to paperwork requirements, all associated with the DGA, as has been diagnosed by the World Bank (2013). In addition, the extremely rigid regulatory framework that leaves limited space for adjustment to changing conditions, has also been criticized (Bitran *et al*., 2014). Finally, the lack of understanding of an institutional integrated system has led to isolated interventions from different departments, sometimes duplicating efforts. This has also been considered as a source of conflict and a barrier to collective management (Bitran *et al*., 2014; World Bank, 2013).

Barrier 4: Trust issues. The evidence shows that there was a lack of trust between water users. This limited the creation of collective water management associations. This barrier was overcome through multiple workshops to bring users together, reflect on the problem, and reach a consensus on the need to jointly manage the aquifer. Additionally, there was distrust between water users and public agencies. For example, the approved statutes and rules of operation for the new groundwater user associations were not registered by the DGA until 4 years later, due to different opinions on the attributions of these associations; this delay limited the association's ability to effectively manage the groundwater. As Powell & Bundhoo (2019), point out, this lack of trust is a barrier to collective action. The existence of trust and trustworthiness of institutions has been linked with successful collective associations (Coleman, 1988; Gambetta, 2000; Ostrom & Ahn, 2009). These results agree with Van Vugt (2002) regarding domestic water demands during droughts where lower levels of trust effectively restrict users from pursuing their collective benefit, i.e. protecting the long-term interests of the community.

Barrier 5: Lack of monitoring techniques and facing financial barriers. The Chilean water code establishes that groundwater user communities are responsible for monitoring and enforcing compliance with water extraction requirements. However, CASUB was formed in 2004 and the remaining associations were only created between 2012 and 2015. Thus, there was no monitoring done by water users, as established in the water code when there were no associations. The DGA tried to fill the gap unsuccessfully, since it did not have the resources to monitor all groundwater extractions (World Bank, 2013), and the State has not had sufficient power to require communities to take action, in particular in terms of data collection, and designing rules to reduce abstraction (Donoso *et al*., 2020; Rinaudo & Donoso, 2019). Only as of 2018, with the latest reform of the water code, has the DGA had greater powers to monitor and enforce water use; however, the DGA was not allocated additional budget to increase its monitoring activity and, thus, has not acted on the increased powers. Thus, the State lacks the financial, technical and human resources to implement all the provisions of the Chilean water law regarding water management and monitoring. This lack of monitoring contributed to the high levels of distrust creating a critical barrier to collective action.

Overall, a major issue is that these problems, theoretically, should not exist. Leaving aside the space for conversation between heterogenous actors, all other issues already have an established protocol written in the Chilean legal framework. For example, for the lack of information, there are formal registries where all water rights should be written, and deadlines for all water rights to be updated to fit current legislation. However, due to different institutional, technical and financial matters, in practice, they have been left unsolved. As has already been stated, the Chilean law is very sophisticated "on paper" but many of its dispositions are left unimplemented (Donoso *et al*., 2020). In this case, there are institutional, technical and financial limitations that translate to information asymmetries, delays in procedures, bureaucratic conundrums and conflictive situations. All of the above factors end up limiting the development of collective groundwater management, in spite of having a legal framework that supports it.

04

Solving Groundwater Management Barriers in Copiapó

Despite all of the barriers mentioned earlier, currently the basin has developed collective groundwater action. For this to happen, formal and informal solutions helped as triggers.

Solution 1: Neutral and technical mediator. The need for a neutral space or forum, where all stakeholders could debate, was solved by the State by hiring an external team. This team was constituted by researchers with the objectives of organizing the groundwater users' communities of the four upper sectors and empower the existing groundwater community, the CASUB. Some key aspects for the development of spaces for agreements were:

- The neutrality and technical confidence provided by the team. The researchers were not linked to the government and authorities. Also, it was an interdisciplinary group including agronomists, lawyers, engineers and economists, among others, thus providing strong technical support. With both of these features, the group provided confidence to the variety of stakeholders.
- An on terrain/field team. Besides the interdisciplinary group of academics and researchers, a local professional team was established in the area, led by a women agronomist. The insertion of the team in the locality, with members who are regular inhabitants, facilitated encounters and opportunities for dialogue.

> *"To clearly delineate the different communities' boundaries and identify their members, a consensus on the list of water users needed to be established"*

Solution 2: Formally establishing common language and spaces in legal documents.
A relevant aspect that triggered collective action was having a collective language and formal representation of all stakeholders established. In detail, the drafting of the legal documents for the new groundwater users' associations, as well as the editing of the existing legal documents, was done using a more colloquial language and format following a bottom up approach. Water users' associations statutes in Chile are complicated to read. They usually copy paragraphs of the water code, incorporate a lot of written information, including a list of all users and details on their water rights. In this case, the statutes were summarized into a shorter document, with less legal jargon, even though it still complies with the normative requirements. The statutes were complemented with a document of procedures that specifies how to put them in practice, and a manual that translates everything into a user's language. This helped develop a common language when discussing water management in the basin. The reformed statutes and rules of operation were approved in a general assembly of CASUB after a series of workshops where they were presented and debated with the users.

Also, to encourage participation, specific seats were established on the board of directors of each community so as to ensure representativity in the main decisions of the association, accounting for the heterogeneity of users. Specific seats were designated for small, medium and large farmers, as well as the mining sector, and the urban uses. Thus, when making regular decisions in the directors' board, small users have voice and a meaningful vote. Nevertheless, small water users pointed out that they still felt excluded from the decision process.[6]

Solution 3: Providing information and cross checking it. To clearly delineate the different communities' boundaries and identify their members, a consensus on the list of water users needed to be established. For this step, the research team undertook the extensive work of reviewing all water registries from the real estate offices (Conservadores de Bienes Raíces) and comparing them with the information provided by the public agency. At the same time, the information was provided to the users for their review, in order to identify differences with their registries, thus achieving a consensus on the final registry. After this stage was completed, all wells were referenced using a geographic information system (GIS). Currently, all water rights and their users have been clearly identified, and an updated registry is in the possession of each groundwater users' community.

Solution 4: Creativity and openness to all ideas. A key for developing collective action in the basin was to use innovative solutions, considering the institutional context. Two extraordinary examples can be mentioned to illustrate this aspect. First, even though the groundwater users' community that was already in place, the CASUB, manages two administrative sectors, the request for developing a unique community for upstream users was denied. Instead, the public authority explicitly indicated the need to develop four separate communities, one for each administrative sector. Complying with this request, four new groundwater users' communities were formed. However, all of them were organized with the same statutes. This allows them to work together, based on goodwill, or at least ensures coherency among the management of the resources in the basin. Currently, sectors 1, 2 and 3 are managed as one community, instead of three different and independent ones.

A second example of the need for creative solutions was the acquisition of surface water rights in the upper section of the basin by the CASUB. The Vigilance Committee did not consider downstream groundwater users when managing the dam's levels. CASUB, as a surface water right holder, now has a say in decisions regarding surface waters which affect their groundwater availability. By buying these surface water rights, they "nested" themselves within the surface water organization.

Solution 5: Building trust. Regaining trust, once it has been lost, is one of the most complicated issues. In Copiapó, the trust among users had to be restored. The triggers for the development of trust among users included:

- Regular meetings over a period of three years, organized by the research team;
- Government not involved in user meetings, allowing users from different economic sectors to moderate their positions while discussing;
- Regular meetings with public authorities informing them of the advances in the constitution of groundwater associations;

Establishment of websites for each community with the information available in a transparent way.

Thus, the proactive involvement of users and public agencies in the problem analysis, increased transparency, and improved communication, building trust between users. A similar conclusion is reached by Parag & Timmons Roberts (2009).

Solution 6: Alliances and long term planning.
One of the most problematic issues faced in the development of a groundwater monitoring strategy is the financial aspect. To solve this, an informal alliance was made with the public sector. The groundwater users' associations developed a strategy to establish to gradually install flowmeters connected to telemetry so as to monitor water extraction, and static and dynamic aquifer levels in real time. To help finance the investment required, the groundwater user associations presented this plan to the public forum to stimulate technological improvement in irrigation works.[7] This program has sequentially co-funded this program together with the users, and currently, all important wells have their own monitoring system, and soon all wells will be monitored.

With all the above, currently the basin has groundwater users' communities working actively in all the six administrative sectors. Each community has representatives and trained directors, empowered in their rights, as well as in their obligations. They now have an updated list of their users' information agreed with the community, as well as the geospatial location and monitoring devices installed in almost all wells. There are still aspects that need to be solved in the basin, such as environmental minimum flows, and indigenous communities' rights that have to be formally incorporated. However, in terms of promotion and development of collective action, the basin has proven to be a successful case to study.

Overall, three aspects can be mentioned as key to the formation of groundwater users' communities in the Copiapó basin. First, the development of long term contracts with technical and neutral parties who act as mediators has been crucial. The research team was initially set up to last two years but ended up lasting three. This time extension was needed because it was not until the end of the first year that the local information was completely gathered, the users started attending the meetings, and the team started gaining credibility and making a solid impression. It took a second year just to solidify these achievements. The establishment of trust cannot be rushed. Short-term relationships cannot build trust that acts as a cornerstone for everything that comes afterwards.

A second aspect relevant for the development of groundwater collective action was the identification and empowerment of good leaders. Since several meetings were held with different groups and places, those who always participated, those who motivated others, and those who were seen as trustworthy among other users, ended up standing out. It turned out, they also had a vision of the basin and an understanding of the need for self-governance. The suggestion of creating a temporal directive was the opportunity for them to be in those positions and to empower others.

Finally, limiting the participation of the administrative authority in the communities' decisions was fundamental. When public agencies have highly bureaucratic standards, self-governance is restricted. In this case, excluding them from the meetings and overall decision-making process led to users finding their voices, finding innovative solutions, and more empowerment for the community. The overall feeling is that the community was not imposed and that they contributed to the process development. The government through its public agencies should only act as a facilitator, either for information or financial resources.

05

Conclusion and Lessons Learned

The Copiapó case represents a sound example of a groundwater basin with many conflicts. It shows a situation where different factors have led to extreme over-extraction. At the same time, poor management is in place in terms of a lack of understanding of connected aquifers, disconnection between surface and groundwater administration, and non-existence of monitoring devices. To add challenges to the situation, an environment of major conflicts and distrust had already been established as the norm. Even though collective management of these ground resources could help solve these issues, specific barriers prevented it.

In the case of Copiapó, the barriers included the existence of highly heterogeneous actors, considering representatives of different economic activities, and the lack of spaces for them to gather. Also, a context of general disinformation regarding their water rights and the water dynamics, high government bureaucracy, and severe trust issues, together with a weak or non-existent monitoring system, all acted as barriers for users to gather and organize themselves.
These elements are also commonly found in other intra-national water basins that have not been able to organize themselves collectively.

Here, it is clear that even though the legal framework has formal protocols to avoid these problematic situations, in practice, many of them are not implemented. Since there is an established protocol, it is difficult to propose alternatives to replace the institutional or technical void without being considered an illegal practice or without encountering opposition. This gap between the tools, institutional arrangements, and information that should be in place and what is really happening, ends up limiting the development of collective water management.

Regardless of these barriers, the basin has been able to develop groundwater collective action. A diversity of actions, with different levels of formality, have been combined and developed in the basin to help with the formation of groundwater communities. Some of the elements that were used include:

- The development of a neutral space or forum, where all stakeholders could debate, encouraged by the hiring of an external and technical consultant team.
- Having a collective language and representation of all stakeholders established formally in the legal documents.
- Clearly identifying all members, their water rights, and establishing a common consensus on this registry.
- Searching for solutions "out of the box" to achieve strategies in a given strict and bureaucratic institutional framework.
- Being consistent and transparent to promote regaining trust between users.
- Specific financial alliances with the public sector to implement a monitoring plan.

The analysis shows the relevance of three elements: first, the existence of a neutral and technical team that acted as mediators; second, the identification and empowerment of leaders; and thirdly, the limitation of the administrative authority in the community's decisions.

At present, the basin has groundwater users' communities working actively in all six administrative sectors. There are still aspects that require solutions in the basin, such as the establishment of environmental securities, and indigenous communities' rights that have to be formally incorporated. However, in terms of promotion and development of collective action, the basin has proven to be a successful case to study and its lessons can be useful for groundwater basins all over the world, as most of the problems and barriers reviewed for the case study can be found in many other basins. Also, the presented case study contains great divergency regarding the multiplicity and heterogeneity of users that it describes, and a highly fragmented institutional system. The above can also account for users and institutional divergencies across different places, and thus, can be useful for enhancing self-managed groundwater communities in other countries as well.

Finally, the use of tools from the Design Principles for Sustainable Management of Common-Pool Resources and the SES framework was key to organizing the analysis and understanding the real barriers and solutions that exist. This analysis and tool are useful, especially after working for years with the case study, where significant variables could go unnoticed. This study can be viewed as a first step towards adapting and expanding the SES Framework in order to consider groundwater management variables.
Further research regarding different groundwater case studies should be conducted in order to strengthen the tool. Nevertheless, key barriers and solutions were identified with the analysis, and these can be useful, not only for improving groundwater governance, but for developing an integrative collective water governance that can hold surface and groundwater as well.

References

Abrigo, G. (2019). *Propuesta metodológica para la organización y funcionamiento de comunidades de aguas subterráneas. AFE para optar al Grado de Magíster en Manejo de Suelos y Aguas.* https://doi.org/10.5354/0717-8883.1955.11040.

Álamos, F. & Peralta, F. (1987). Análisis y Evaluación de los Recursos Hidrogeológicos del Valle del Río Copiapó. *Dirección General de Aguas (DGA) Del Ministerio de Obras Públicas (MOP).*

______. (1995). Análisis y Evaluación de los Recursos Hídricos en el Valle del Río Copiapó. *Dirección General de Aguas (DGA) Del Ministerio de Obras Públicas (MOP).*

Bauer, C. J. (2015). Water conflicts and entrenched governance problems in chile's market model. Water Alternatives.

Bitran, E., Rivera, P. & Villena, M. J. (2014). Water management problems in the Copiapó Basin, Chile: Markets, severe scarcity and the regulator. *Water Policy, 16*, pp. 844–863. https://doi.org/10.2166/wp.2014.107.

Coleman, J. S. (1988). Social Capital in the Creation of Human Capital. *American Journal of Sociology.* https://doi.org/10.1086/228943.

Cox, M., Arnold, G. & Villamayor-Tomás, S. (2010). A review of design principles for community-based natural resource management. *Ecology and Society*, 15(4). https://doi.org/10.5751/ES-03704-150438.

______. (2016). Design principles in commons science: A response to "Ostrom, Hardin and the commons" (Araral). *Environmental Science and Policy*, 61, pp. 238–242. https://doi.org/10.1016/j.envsci.2016.03.020.

CSIRO. (2015). Plan de gestión integrada para la cuenca del Copiapó, Fase 1. *Serie de Informes Técnicos (SIT) Dirección General de Agias (DGA) Del Ministerio de Obras Públicas (MOP) Fundación CSIRO Chile*, 179. Retrieved from http://www.dga.cl/estudiospublicaciones/Series documentales/Informe_Final_para_Empaste_01_10_2015.pdf.

DGA (Dirección General de Aguas). (1993). Situación de los Recursos Hídricos III-IV Regiones. *Dirección General de Aguas (DGA) Del Ministerio de Obras Públicas (MOP), Enero-Dici*.

______. (2004). *Diagnostico y Clasificacion de los cursos y cuerpos de agua segun objetivos de calidad. Cuenca del río Copiapó. Dirección General de Aguas (DGA) Ministerio de Obras Publicas, Gobierno de Chile.*

DICTUC. (2010). *Analisis integrado de gestion en cuenca del rio Copiapo, Chile, Informe final tomo 1*.

Donoso, G. (2014). Integrated water management in Chile. *In Integrated Water Resources Management in the 21st Century: Revisiting the paradigm*. https://doi.org/10.1201/b16591-16.

______. (2018). Overall Assessment of Chile's Water Policy and Its Challenges. *Water Policy in Chile*, pp. 209–219. https://doi.org/10.1007/978-3-319-76702-4_14.

Donoso, G., Lictevout, E. & Rinaudo, J. D. (2020). Groundwater Management Lessons from Chile. *Sustainable Groundwater Management. Global Issues in Water Policy*, 24, pp. 481–509. https://doi.org/10.1007/978-3-030-32766-8_25.

Ebenhöh, E. (2007). Designing Agent-based Models of Water Management Regimes using the IAD Framework. *The Challenge of Self-Governance in Complex, Globalizing Economies*.

Fuster, R., Gonzáles, L., Morales, L., Cerda, C., Hernández, J., Sotomayor, D. & Valdebenito, J. (2010). Gestión Integrada de los recursos hídricos en Chile. *Biblioteca Del Congreso Nacional, a Través de Fondos Del Banco Interamericano Del Desarrollo. Departamento de Ciencias Ambientales y Recursos Naturales Renovables de La Facultad de Ciencias Agronómicas de La Universidad de Chile*, 395.

Gambetta, D. (2000). Unknown - Unknown - aefi-idrv. https://doi.org/10.1.1.24.5695.

Golder Associates. (2006). Diagnóstico de los recursos hídricos de la cuenca del Río Copiapó y proposición de un modelo de explotación sustentable, 245. Retrieved from https://research.csiro.au/gestion-copiapo/wp-content/uploads/sites/216/2018/01/062-2006-Diagnostico-de-recursos-hidricos-en-Copiapo-Golder.pdf.

Gorelick, S. M. & Zheng, C. (2015). Global change and the groundwater management challenge. *Water Resources Research*, 51, pp. 3031–3051. https://doi.org/10.1002/2014WR016825.

Hardin, G. (1968). The Tragedy of Commons. Science. https://doi.org/10.1126/science.162.3859.1243.

Heikkila, T., Schlager, E. & Davis, M. W. (2011). The Role of Cross-Scale Institutional Linkages in Common Pool Resource Management: Assessing Interstate River Compacts. *Policy Studies Journal*, 39(1), pp. 121–145. https://doi.org/10.1111/j.1541-0072.2010.00399.x.

Herrera, M., Candia, C., Rivera, D., Aitken, D., Brieba, D., Boettiger, C. & Godoy-Faúndez, A. (2019). Understanding water disputes in Chile with text and data mining tools. *Water International*, 44(3), pp. 302–320. https://doi.org/10.1080/02508060.2019.1599774.

IPLA (Ingeniería y Planificación). (1984). *Balance Hidrológico Nacional Regiones III y IV.*

______. (1994). Análisis de Uso Actual y Futuro de los Recursos Hídricos de Chile, Regiones III-IV. *Dirección General de Aguas (DGA) Del Ministerio de Obras Públicas (MOP).*

Jouravlev, A. (2005). Integrating Equity, Efficiency and Environment in the Water Allocations Reform. In *Presentation at the*

International Seminar of Water Rights Development in China. Beijing.

Kinzelbach, W., Bauer, P., Siegfried, T. & Brunner, P. (2003). Sustainable groundwater management - Problems and scientific tools. *Episodes*, 26(4), pp. 279–284. https://doi.org/10.18814/epiiugs/2003/v26i4/002.

Kiser, L. L. & Ostrom, E. (1982). The Three Worlds of Action: A Metatheoretical Synthesis of Institutional Approaches. *Strategies of Political Inquiry*, pp. 179–222.

Lam, W. F. & Ostrom, E. (2010). Analyzing the dynamic complexity of development interventions: Lessons from an irrigation experiment in Nepal. *Policy Sciences*, 43, pp. 1–25. https://doi.org/10.1007/s11077-009-9082-6.

Lopez-Gunn, E. (2003). The Role of Collective Action in Water Governance: A Comparative Study of Groundwater User Associations in La Mancha Aquifers in Spain. *Water International*, 28(3), pp. 367–378. https://doi.org/10.1080/02508060308691711.

Lopez-Gunn, E. & Martínez, L. (2006). Is self-regulation a myth? Case study on Spanish groundwater user associations and the role of higher-level authorities. *Hydrogeology Journal*. https://doi.org/10.1007/s10040-005-0014-z.

Martínez, L. & Hernández, N. (2003). The role of groundwater in Spain's water policy. *Water International*, 28(3), pp. 313–320. https://doi.org/10.1080/02508060308691704.

McFarlane, D. & Norgate, T. (2012). Summary report on Copiapó water yields and demands. A report submitted to AusAID as part of the study: Copiapó River Basin, Chile – analysis study of shortfalls in water rights, industrial usage and social requirements. *CSIRO*, pp. 1–66. Retrieved from https://publications.csiro.au/rpr/download?pid=csiro:EP126400&dsid=DS4.

McGinnis, M. D. (2011). An Introduction to IAD and the Language of the Ostrom Workshop: A Simple Guide to a Complex Framework. *Policy Studies Journal*. https://doi.org/10.1111/j.1541-0072.2010.00401.x.

Meinzen-Dick, R. (2007). Beyond panaceas in water institutions. *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.0702296104.

______. (2014). Property rights and sustainable irrigation: A developing country perspective. *Agricultural Water Management*, 145(0), pp. 23–31. https://doi.org/http://dx.doi.org/10.1016/j.agwat.2014.03.017.

Muñoz, J. (2010). Aplicación del concepto de uso previsible en la constitución originaria de derechos. *Revista Vertiente, 11*(Capítulo Chileno A.G.).

Oakerson, R. J. & Parks, R. B. (2011). The Study of Local Public Economies: Multi-organizational, Multi-level Institutional Analysis and Developmentp. *Policy Studies Journal*, 39(1), pp. 147–168.

Ostrom, E. (1990). *The Evolution of Institutions for Collective Action. Political Economy of Institutions and Decisions*. https://doi.org/10.1017/CBO9780511807763.

______. (2000). Collective Action and the Evolution of Social Norms. *The Journal of Economic Perspectives*, 14(3), pp. 137–158.

______. (2007). A diagnostic approach for going beyond panaceas. *Proceedings of the National Academy of Sciences of the United States of America*. https://doi.org/10.1073/pnas.0702288104.

______. (2011). Background on the Institutional Analysis and. *Policy Studies Journal*, 39(1), pp. 7–27. https://doi.org/10.1111/j.1541-0072.2010.00394.x.

______. (2015a). *Governing the commons: The evolution of institutions for collective action. Governing the Commons: The Evolution of Institutions for Collective Action*. https://doi.org/10.1017/CBO9781316423936.

______. (2015b). *Governing the commons*. Cambridge university press.

Ostrom, E. & Ahn, T. K. (2009). The Meaning of Social Capital and Its Link to Collective Action. In Svendsen, G. T. & Svendsen, G. L. (eds.) *Handbook on Social Capital*, pp. 17–34. Edward Elgar Publishing.

Ostrom, E., Janssen, M. A. & Anderies, J. M. (2007). Going beyond panaceas. *Proceedings of the National Academy of Sciences of the United States of America*, 104(37), pp. 15176–15178. https://doi.org/10.1073/pnas.0701886104.

Ostrom, E., Lam, W. F., Pradhan, P. & Shivakoti, G. P. (2011). *Improving irrigation in Asia: Sustainable performance of an innovative intervention in Nepal. Improving Irrigation in Asia: Sustainable Performance of an Innovative Intervention in Nepal*. https://doi.org/10.4337/9780857938022.

Ostrom, V. (1991). Polycentricity: The Structural Basis of Self-Governing Systems. In *The Meaning of American Federalism: Constituting a Self-Governing Society [Vincent Ostrom]* (pp. 223–244). San Francisco: ICS Press.

Parag, Y. & Timmons Roberts, J. (2009). A battle against the bottles: Building, claiming, and regaining tap-water trustworthiness. *Society and Natural Resources*, 22(7), pp. 625–636. https://doi.org/10.1080/08941920802017248.

Poteete, A. R., Janssen, M. A. & Ostrom, E. (2010). *Working together: Collective action, the commons, and multiple methods in practice. Working Together: Collective Action, the Commons, and Multiple Methods in Practice*.

Powell, J. & Bundhoo, D. (2019). *Negotiating a way towards consilience in managing conflicts over commons: a multi-stakeholder dialogue Report*.

PUC (Pontificia Universidad Católica de Chile). (2014). *Informe Final Programa: Capacitación y Apoyo a Comunidades de Aguas Subterráneas en el Valle de Copiapó*. Santiago.

Rinaudo, J. D. & Donoso, G. (2019). State, market or community failure? Untangling the determinants of groundwater depletion in

Copiapó (Chile). *International Journal of Water Resources Development*, 35(2), pp. 283–304. https://doi.org/10.1080/07900627.2017.1417116.

Rivera, Daniela. (2015). Diagnóstico jurídico de las aguas subterráneas. *Ius et Praxis*, 21(2), pp. 225–266.

______. (2018). Alumbrando conflictos: disponibilidad y asignación de derechos de aguas subterráneas en la jurisprudencia chilena. *Revista de Derecho (Valdivia)*, 31(1), pp. 159–183. https://doi.org/10.4067/s0718-09502018000100159.

Rivera, Daniela, Del Río, C., Donoso, G. & Molinos-Senante, M. (2020). Conflictividad judicial de aguas en Chile: caracterización y propuestas para mejorar su prevención y resolución. *Propuestas Para Chile 2019. Centro de Políticas Públicas UC*.

Rivera, Diego, Godoy-Faúndez, A., Lillo, M., Alvez, A., Delgado, V., Gonzalo-Martín, C. & García-Pedrero, Á. (2016). Legal disputes as a proxy for regional conflicts over water rights in Chile. *Journal of Hydrology*. https://doi.org/10.1016/j.jhydrol.2016.01.057.

Ruttan, L. M. (2006). Sociocultural Heterogeneity and the Commons. *Current Anthropology*, 47(5), pp. 843–853. https://doi.org/10.1086/653807.

______. (2008). Economic Heterogeneity and the Commons: Effects on Collective Action and Collective Goods Provisioning. *World Development*, 36(5), pp. 969–985. https://doi.org/10.1016/j.worlddev.2007.05.005.

SITAC. (2008). Modelo Hidrogeológico Cuenca Río Copiapó, Sector Ramadillas - La Puerta, Proyecto Caserones. Servicios de Ingeniería y Construcciones SITAC S.A.

Tang, S. Y. (1991). Institutional Arrangements and the Management of Common-Pool Resources. *Public Administration Review*, pp. 42–51. https://doi.org/10.2307/976635.

Troncoso, R., Pérez, Y., Castro, R., Lorca, M. E., Vega, N. & Al., E. (2012). Evaluación hidrogeológica de la cuenca del río Copiapó, con énfasis en cuanti cación, dinámica y calidad química de los recursos hídricos super ciales y subterráneos. *Servicio Nacional de Geología y Minería (SERNAGEOMIN)*.

Van-Vugt, M. (2002). Central, Individual, or Collective Control? *American Behavioral Scientist*. https://doi.org/10.1177/0002764202045005004.

Wang, C. & Segarra, E. (2011). The economics of commonly owned groundwater when user demand is perfectly inelastic. *Journal of Agricultural and Resource Economics*, 36(1), pp. 95–120.

World Bank. (2011). Diagnóstico de la gestión de los recursos hídricos. Chile. *Departamento Del Medio Ambiente y Desarrollo Sostenible*. https://doi.org/10.1029/2001WR000748

______. (2013). Estudio para el mejoramiento del marco institucional para la gestión del agua. Chile. *Departamento Del Medio Ambiente y Desarrollo Sostenible*.

Zhang, Y. (2018). Crossing the divide: an integrated framework of the commons. Evolutionary and Institutional Economics Review, 15, pp. 25–48. https://doi.org/10.1007/s40844-017-0077-2.

______. (2019). Governing the water commons in China: from historical oriental despotism to contemporary fragmented hydraulic state. *International Journal of Water Resources Development*, 35(6), pp. 1029–1047. https://doi.org/10.1080/07900627.2018.1508989.

______. (2020). How did the lost Shangri-La get lost? The tragedy of the groundwater commons in Lijiang, China. *Water*, 12(11). https://doi.org/10.3390/w12113131.

Notes

1. Sector 1 Upstream of the Lautaro Reservoir; Sector 2 Lautaro Reservoir- La Puerta; Sector 3 La Puerta- Mal paso; Sector 4 Mal Paso-Copiapó; Sector 5 Copiapó-Piedra Colgada; Sector 6 Piedra Colgada-Desembocadura (flows into the ocean).
2. DGA *Sistema Nacional de Información del Agua*, SNIA (National Water Information System), Files NC-0302-149 (sectors 5 and 6), 150 (sector 4), 151 (sector 3), 152 (sector 2), 153 (sector 1).
3. Most water rights were formally registered between 1985 and 1988, reflecting the time when historical rights began to be inscribed in the Real Estate Conservators books.
4. Due to a legal reform passed in 2005.
5. *Consejo Asesor Regional de Recursos Hídricos* (CARRH).
6. Even though the legal documents allow for an effective participation of all users, since votes are proportional to the size of water rights, small users feel excluded from the decision process.
7. Law N. 18,450, *Ley de Fomento a la Inversión Privada en Obras de Riego y Drenaje* (Law for the Promotion of Private Investment in Irrigation and Drainage) is an instrument to stimulate technological improvement in irrigation works. Over the years, it has incorporated off-farm projects, such as works for the distribution of water in a community, and thus, allows supporting the investment in groundwater monitoring devices with subsidies.

3

Groundwater Governance for Conflict-Affected Countries

Amy Hardberger and Bruce Aylward

Amy Hardberger, Texas Tech University School of Law, Lubbock TX, USA.
e-mail: amy.hardberger@ttu.edu
Bruce Aylward, Mercy Corps, Washington DC, USA.
e-mail: baylward@mercycorps.org

Abstract

Water security is critical in developing countries that face protracted crises, displaced peoples, food insecurity and climate vulnerability. Groundwater can help regions burdened with these issues; however, unregulated groundwater extraction can lead to unintended long-term consequences including aquifer depletion, decreased surface water flows and environmental degradation. This paper focuses on conflict-affected states in arid and semi-arid countries of Africa and the Middle East with selected case studies in Jordan and Kenya. Governance with best practices should include an array of stakeholders such as water managers, local policymakers, donors, investors and communities conversations as part of humanitarian/development work and should consider ongoing conflict, high numbers of cross-border refugees, displaced peoples, lack of financial resources and potential political corruption. Key outcomes include specific data and regulatory recommendations that incorporate present legal regimes, permitting practices, groundwater resources, and water tenure concerns. Recommendations include how communities and NGOs can proactively partner with government to develop and improve information and management systems in the face of the considerable challenges faced in these settings.

Keywords

Groundwater, food security, groundwater management, Africa

01
Introduction

In these days of pandemics and medical terminology, it may be possible to suggest that the challenge of social and economic development in many of the world's less developed countries has undergone a long, slow mutation – and not for the better. In areas with displaced people, prolonged periods of crisis and food insecurity, lack of water is often at the heart of the conversation.

Access to drinking and productive water is low across developing countries and efforts to meet Sustainable Development Goal (SDG) targets continue to fall short. Groundwater can solve many of these concerns while increasing food security; however, unregulated extraction can lead to unintended, long-term consequences including aquifer depletion, decreased surface water flows downstream and environmental degradation. Low rainfall in these areas and threats from climate change generate limited recharge capacity.

In some countries, large-scale groundwater development has led to short-term benefits, but dwindling reserves. In others, groundwater has yet to be tapped. The timing for review and creation of improved groundwater governance is ideal in both settings. Conflict-affected states in arid and semi-arid countries of Africa and the Middle East, such as Jordan and Kenya, provide examples of each of these realities.

With over 60% of the country's water supply coming from groundwater, Jordan is challenged by over abstraction and the need to move water from existing agricultural users to other sectors. In contrast, Kenya has untapped resources and large populations without sufficient access to water, particularly for productive purposes. While both countries have thoughtful aspects to their governance approaches, each could borrow missing aspects from one another. In both cases, management is imperative; however, structural realities including conflict, refugees, corruption and lack of capacity challenge the ability to implement policies successfully. Solutions may be found in partnerships between government, non-government organizations (NGOs), regional management, donor investors and community stakeholders as part of humanitarian and development work.

1.1. The Context: Triple Nexus and Groundwater Governance

In the 20th century, there were developing regions and there were natural disasters as there are now. The latter sometimes occurred in the former, but also occurred in developed regions. Similarly, there was conflict between and within states that manifested itself in regional conflict, civil war and other lower-intensity conflict. Perhaps hindsight is not 20/20, but it seems that back then each of these problems had a clear cause, a distinct geography and motivated specific expertise to find solutions. The development community – multilaterals, bilaterals, governments, and NGOs – took on the development challenge, the United Nations (UN) and humanitarian NGOs took on disasters and the UN and member states took on peace-building.

Over the past 20 years, rising levels of armed conflict and the protracted nature of this conflict – along with increasingly frequent and severe natural disasters – are layered on top of lackluster economic progress to create a particularly complex challenge. Practitioners have labelled this the "triple nexus", referring to the need to blend development, humanitarian and peacebuilding assistance and to do so in an intelligent, coordinated and effective manner in order to address what is now called amongst other names, "fragility" (Petryniak *et al.*, 2020). In this new world the objective is often framed as building resilience, in order that communities and vulnerable populations might be able to absorb, adapt to and transform their circumstances in the presence of repeated complex and long-lasting stresses and shocks.

This paper examines the link between this strand of human history and the changing context of how to best govern, manage and use groundwater resources. It is common knowledge that the exploitation of groundwater resources is a perennial problem in arid and semi-arid areas of developed economies. The demand for water as populations grow and economies flourish drives the diversion, damming and extraction of surface and groundwater inexorably from low-cost to high-cost supplies. Moreover, as the saying goes, "water runs uphill to money" - meaning that higher value users of water ultimately deprive lower value users of that same water – either by administrative fiat, market transactions or corrupt behavior. That economic and political power drive water entitlements and allocations, just like other resources, is not a surprise and is not limited to developed regions.

The question addressed in this paper is how to achieve some measure of effective groundwater governance in the presence of the triple nexus. Given the context, governance solutions may not be first best options. The problem is not optimization of groundwater use but rather understanding its use and developing, albeit gradually, the ability to manage this use. A two-pronged approach consists of finding entry points to the measurement, monitoring and management of groundwater whilst promoting a governance framework that can evolve towards effective management as and when enabled by the surrounding context.

1.2. The Peacebuilding, Development, and Humanitarian Context

In this section, regional trends in conflict and development are examined, alongside prospects for future humanitarian needs based on vulnerability to climate change. Particular attention is given to the Middle East and North Africa (MENA) and Sub-Saharan Africa (SSA) regions. These two regions include numerous countries designated as fragile or conflict affected states (FCS) by the World Bank and form large portions of the portfolios of international humanitarian and development NGOs.

In 2019, global organized violence consisted of over 150 conflict events (at least 25 fatalities) for a total of 75,000 killings (Pettersson & Öberg, 2020). The trend in recent years is toward increasing numbers of conflicts, although fatalities have fallen from the 2011 peak during the outbreak of the Syrian civil war. These events are classed as state-based armed conflict, non-state violence and one-sided violence. State-based conflict, which accounts for two-thirds of fatalities, is particularly prevalent in Africa with the number of conflicts in the Middle East rising in recent years. Non-state violence (two-sided violence not involving the state) is now more prevalent (44% of total events) than state-based violence; these events have grown rapidly in the last decade, primarily in Africa and the Middle East. One-sided violence conflict events vary annually in number and made up 7% of total fatalities in 2019. Africa accounts for the overwhelming majority of one-sided violence, followed by the Americas and the Middle East. In sum, MENA and SSA are beset by growing levels of organized violence.

During the 2000 to 2010 period fairly rapid rates of improvement in the Human Development Index (HDI) were observed in many developing regions, including MENA and SSA countries (UNDP, 2018). During this period the regions further behind gained ground on those that were more advanced. Since 2010, however, progress has stalled. Annualized rates of increase in HDIs for SSA and MENA countries retreated significantly. For the eight MENA countries in which Mercy Corps is present, which include some of the worst conflict-affected countries, the HDI level actually decreased in absolute terms, since 2010. Conflict appears to be taking a toll on development.

Against this backdrop of increasing conflict and waning development performance is the prospect of future increases in insecurity and crises attributable to climate change. According to the United Nations, climate-related disasters (including floods, droughts and storms) accounted for more than 90% of the world's disasters between 1998-2017 (CRED & UNISDR, n/d). Over US$ 2.2 trillion or 77% of total economic losses from these disasters were climate-related. While the absolute economic value of losses in low income countries is less than in high income countries – in part due to the value of their respective infrastructure – the portion of gross domestic product (GDP) that is lost to climate-related disasters (1.8%) for low income countries is much greater than in high income countries (0.4%) (CRED & UNISDR, n/d). The variation between regions in vulnerability to climate change, as measured by Notre Dame Global Adaptation Index (ND-GAIN), is quite stark (Chen *et al*., 2015). South Asia and SSA are by far the most vulnerable regions with MENA exhibiting somewhat less vulnerability. Notably, the conflict-affected SSA countries in which Mercy Corps is present are more vulnerable than other regions by a considerable amount, and show little improvement between 1995 and 2018. Clearly, as climate change proceeds the vulnerability of communities in these already conflict-affected and development-challenged regions is only likely to worsen.

1.3. Water Scarcity, Governance and the Challenge of Groundwater Management in the P resence of the Triple Nexus Challenge

Having established that the confluence of development, humanitarian and conflict issues is particularly acute in MENA and SSA, we turn to examine the extent of water scarcity in these two regions. Kummu *et al*. (2016) carried out analysis of water shortage (water available per capita) and water stress (portion of water available being consumed by humans) across the globe. The combination of these two factors constitutes water scarcity. Their results demonstrate that MENA, along with Central Asia, is one of the most water scarce regions of the world. A large portion of the MENA region has the highest level of water scarcity, recording both high shortage and stress. Countries in the Sahel, Horn and East Africa, as well as those in southern Africa display moderate and high water shortage, but not water stress – as their usage of available surface and groundwater remains relatively low. SSA and particularly MENA are thus also beset by the drivers of water scarcity.

What prospects do these regions have of managing their water resources, particularly groundwater? This will depend on the ability of nations to formulate, approve and implement laws, regulations and administrative policies, or the capacity of countries for self-governance. Governance indicators from the World Bank's Country Policy and Institutional Assessment (CPIA) framework and Transparency International's Corruption Perceptions Index (TI-CPI), provide a window into the likely capacity of regions and countries for successful management of a common resource like groundwater (World Bank, 2020, Transparency International, 2020). Across relevant indicators from these datasets, SSA, MENA, score poorly, lagging the other regions with the exception of South Asia. However, Jordan, and to a lesser extent Kenya, score well compared to their peers. Jordan and Kenya have relatively more governance capacity than their peers. The case studies in this paper investigate how this translates into the realm of groundwater governance.

This quick review of the challenges of the triple nexus, water scarcity and governance suggests that the most fragile and conflict-affected countries have low development levels, high conflict levels and high vulnerability to climate change and associated shocks, stresses and natural disasters. For the arid and semi-arid areas that make up MENA and large portions of SSA, there is a dependence on groundwater sources to meet human needs for food and drinking water.

In MENA, due to higher income and development levels, groundwater sources have already been tapped and are being used at levels well above their replenishment levels. This poses questions about the longevity of these resources and the costs of alternative sources and/or conservation measures. For SSA, with the exception of portions of the Horn and southern Africa, groundwater use remains relatively underdeveloped.

These two regions – exemplified by the cases of Jordan and Kenya – prompt the question of how best to govern and use the groundwater resource. In MENA the manifestation of this question is whether, and if so how, to scale back groundwater extraction. For SSA, the issue is where, and if so how, to increase groundwater extraction.
This paper does not address the question of whether groundwater extraction should or should not be scaled back or developed in these regions. This normative choice is for each country to make within the context of national policy. Here, we focus on the tools of governance in the context of the triple nexus.

02

Groundwater Governance

In practice, groundwater governance includes a system by which the permission to use groundwater is granted by the relevant authority, and this use is measured, monitored and managed against approved terms and conditions for groundwater extraction and use. A governance system may also include regulations related to other objectives such as recharge rates, human rights, water transfers, water conflict, water quality, surface water management and environmental uses.

Groundwater has long been regarded as a common pool resource, meaning a resource from which it is hard to exclude potential consumers, and the consumption of which by one consumer reduces the amount available to another (Ostrom & Ostrom, 1972). In the short-run groundwater better fits the definition of a public good given that there is plenty of water to meet all demands placed on the resource. However, in the long-run one person's use of groundwater will subtract from that available to another (Aylward, 2016; Hardin, 1968).

> *"Once usage exceeds the recharge rate, the over-draft on the aquifer will lead to the depletion of the resource if left unaddressed by collective action"*

As discussed later, the extraction of groundwater today for agricultural use in Jordan makes this water unavailable to meet urban demand for household water needs in the future. Common pool resources left to open access are prone to market failure and inefficient and inequitable usage, and thus call for collective action in their management (Randall, 1983). Once usage exceeds the recharge rate, the over-draft on the aquifer will lead to the depletion of the resource (and declining water table levels and water quality as it is drafted downwards) if left unaddressed by collective action.

Society has evolved a number of institutional arrangements to manage common pool resources. These revolve around establishing institutional mechanisms for excluding (and limiting) users from accessing and using groundwater. For groundwater, relevant arrangements include:

- Centralized arrangements – collective management by public authorities at the national or sub-national scale (e.g., state/province).
- Decentralized or devolved arrangements – delegation of management power and authority to a region, often at the scale of the groundwater basin
- Common property management regimes – user groups setting their own rules for managing the resource
- Markets – setting the scale for groundwater use (the "cap"),

distributing permits to users and then letting buyers and sellers trade to meet their needs (the "trade")

Finally, there are polycentric arrangements, in which authority and roles in groundwater management are distributed across different groups. For example, groundwater permits are managed centrally, or by individual regions, but market transactions are used to reallocate permits under a fixed or variable groundwater use limit (or cap). This system avoids hierarchical power structures in favor of distributing roles and responsibility in order to enhance accountability, transparency, legitimacy and public participation, which can be beneficial in the management of common pool resources such as groundwater.

Central questions in governing common pool resources are focused on: who controls the allocation of rights of access and use to the resource; how these rights are transferred; and who is charged with managing the resource (Schlager & Ostrom, 1992; Aylward *et al*., 2009). The answers to these questions often emerge from the governing institutional arrangement.

Some countries, like Israel, opt for a centralized approach, where all waters belong to the state and are managed at that level. Other countries, like the United States, prefer a more localized approach based on the understanding that hydrologic and regional demands vary based on location. Within the United States, some jurisdictions manage groundwater at the state level whereas others, like California, manage it at the aquifer level and still others, like Texas, have adopted a hyper-regional approach where the lowest level of government regulates groundwater.

Generally, groundwater management is a process by which permission to use water is granted to users by the relevant authority. This permission most often takes the form of a right to use water, providing the rights holder with the legal right to access a quantity of water, but not vested ownership of the water itself. Gaining a water right can occur several ways. In most instances, someone desiring a right would apply to the regulatory authority. An application includes the quantity of water requested, where it will be used, for what purpose and during what times of the year. Some application systems automatically grant a groundwater right to the surface owner whereas others may treat them like any other applicant.

> *"Newer theories of governance, including integrated water management, advocate for a holistic approach that integrates planning for source water extraction with considerations of land, climate change and urban runoff with the goal of capturing co-benefits in related economic sectors"*

A permit generally refers to a vested property right that has limited ways it can be terminated; however, a license is revocable. Limitations on the right may also vary in relation to neighboring rights. Legal alternatives like reasonable use or correlative rights both seek to ensure that one user is not pumping to the detriment of another. Most water regimes are focused on human needs and neglect the environment as an essential water user. A key governance challenge is for regimes to be protective of the resource, while responding to societal objectives for water use.

Groundwater regulatory schemes will differ based on the desired outcomes. For some, the focus might be on the rights of the applicants, whereas others may set a total pumping cap to ensure aquifer longevity. Another alternative is to tie pumping limits to spring flow or environmental flows. Newer theories of governance, including integrated water management, advocate for a holistic approach that integrates planning for source water extraction with considerations of land, climate change and urban runoff with the goal of capturing co-benefits in related economic sectors.

A defined list of reasonable or beneficial uses will assist in allocation decisions, particularly if these uses are ranked by priority. A detailed understanding of quantity ranges for each use will assist with management. For example, agriculture is generally a high priority use; however, the reasonableness of water use can vary widely depending on factors such as type of crop, method of irrigation, and land preparation.

03
Case Studies

3.1. Kenya Case Study

3.1.1. Local Conditions

The Republic of Kenya straddles the equator on the eastern coast of Africa. Kenya is a parliamentary democracy, with a free market economy largely dependent on tourism and trade in agriculture products. Prior to the coronavirus outbreak in 2020, Kenya's economy was improving after a series of challenging events including the 2013 Westgate Mall and subsequent terrorist attacks, periodic droughts, and political unrest such as the 2017 Laikipia land invasions (The Guardian, 2013; 2017). Fifty-nine percent of Kenyans have access to basic water services and only 29% have access to sanitary services (WHO & UNICEF, 2019).

Rainfall is highly variable with 80% of the country categorized as arid and semiarid. Climate change models show 1°C increase between 1960 and 2003, with most warming taking place in the 'long rains' season of March (Thornton, 2010).

Conflict is common throughout the country, but is particularly prevalent in the Rift Valley, Nairobi, the peripheral pastoralist drylands, and the coast. Violence is often the result of ethnic conflict, poverty, restricted access to pastoral resources, border tensions, easy access to small arms, and cyclical political instability. These areas also see conflict associated with land and resource access and human/wildlife conflicts, which increase during drought cycles. The prevalence of conflict in Kenya inhibits the country's ability to progress economically and effectively develop resources in ways that benefit the larger community.

3.1.2. Kenya's Groundwater Resources

Geologically, Kenya is divided by the great Rift Valley and dominated by volcanic formations in many areas. Groundwater quantity and quality is greatly affected by subsurface chemistry and physical properties. Groundwater quality is a challenge in Kenya. In Central and Western Kenya, groundwater is generally soft with moderate alkalinity. Groundwater in coastal, eastern and northeastern regions is saline and of poor quality (Mwango *et al.*, 2004)

Groundwater is used for public water supply, agriculture, domestic, industry, and livestock. Kenya is currently using a small fraction of the available groundwater. A 2004 study stated that "the total present groundwater abstraction rate in Kenya is estimated at 57.2 million m^3/year. Total safe abstraction rate in Kenya is estimated to be 193 million m^3/year" (Mwango *et al.*, 2004).

One challenge in managing Kenya's groundwater is lack of knowledge about underground water resources. In 2013, UNESCO led a project that sought to better understand groundwater in the very arid region of Turkana. The Lodwar and Lotikipi aquifer basins were located using satellites and radar. The two deep aquifers (over 300 meters) are estimated to contain at least 250 billion m^3 of water (Radar Technologies International, 2013). This is over 4,000 times the entire country's annual groundwater abstraction rate as cited above. However, the water was subsequently found to have high salinity, limiting the usefulness of the aquifer. In 2019, a Saudi Arabian company was contracted by Turkana County to install desalination plants and there have been discussions about transporting the water to oil prospectors via pipeline.

The Merti aquifer in the northeastern part of the country extends from northeast of Habaswein into Somalia (Mwango *et al.*, 2004). Although a portion of the aquifer is located in Somalia, there is no transboundary agreement in place. One of the most important sources of freshwater in northern Kenya, this aquifer is the primary water source for 350,000 to 450,000 refugees at the Dadaab camps. This water dependency has driven research about the aquifer in order to better understand its storage and recharge. In 2014, the aquifer was being researched as a municipal water supply for the city of Wajir, with drinking water to be supplied through a 120 km pipeline, which raised concerns about intrusion of bounding saline water.

Previous studies estimated groundwater recharge of the Merti aquifer to be quite low making it a "fossil aquifer". More recent studies proposed the recharge rate to be much higher than originally thought, underscoring the need for good science to enable effective management (Blandenier *et al.*, 2016). In 2014, the International Groundwater Resources Assessment Centre (IGRAC) conducted a Managed Aquifer Recharge project on the Merti, which found that the aquifer could benefit from enhanced recharge using injection wells.

The Nairobi Aquifer System (NAS) is perhaps under the most stress of any of Kenya's aquifers. The NAS covers an area of 6,500 km^2, much of which is overlain by the city. While much of Nairobi is supplied by the Tana River, there were over 4,000 boreholes in 2009 making this the most abstracted aquifer in Kenya, also vulnerable to pollution and drought. Boreholes that used to be 80 meters deep now need to extend 400 meters to reach water (Reuters, 2018). In addition to the pumping, up to 50% of the water may be lost in transmission due to a deficient distribution system.

The Tiwi and Baricho are smaller coastal aquifers that supply water to Kenya's south coast, primarily for municipal water supply. Currently, neither aquifer appear to be over-extracted, but the Baricho has higher vulnerability to pollution due to its alluvial nature. Limited data is available for these. In addition to the coast, the cities of Naivasha, Nakuru, Wajir, Mandera, and Lodwarand as well as rural centers are heavily dependent on groundwater resources. Hand pumps are common in villages across the country.

Long-term sustainability of aquifers in Kenya is not solely controlled by careful pumping. Government authorities must also understand the linkage between land use and groundwater. Protection of recharge zones as well as water quality risks is essential. In 2014, the Kenya Groundwater Mapping Programme (KGMP) was launched. The goal of the project is to build local capacity to effectively and sustainably manage groundwater resources by improving the scientific knowledge about groundwater.

3.1.3. Current Groundwater Governance

In Kenya, water resources are vested in the state (Table 3-1). Water use is subject to approval and a water permit that typically defines type of use, the amount authorized, and the duration of use. Despite this legal structure, groundwater is often perceived to be a private resource that can be used by the surface property owner, which puts it at risk of being overused as a common pool resource with a focus on short-term gains.

Initially, national water management in Kenya focused on making potable water available to all households by the year 2000; however, the 1999 National Water Policy shifted the responsibility for water supply to the local level and focused the national government on regulatory management.
The Water Act of 2002 further separated the obligations of supply from regulation, decentralized many functions to lower levels, shifted focus to implementation, and provided a role for non-governmental entities. The Act created the Water Resources Management Authority, which regulates the ownership and control of water and makes provisions for the conservation of surface and groundwater.

Part II of the Act states that all water is vested in the state. The Minister, assisted by the Director of Water, is permitted to exercise agency over water in accordance with other provided provisions. Decisions about water must be focused on conservation and the "proper use of water." Groundwater does not have its own regulatory framework, but is managed as part of water resources generally. This can be problematic due to the unique nature of groundwater.

To assist with the goals of the Act, Part III establishes the Water Resources Management Authority (WRMA), which consists of a Chairman and ten appointed members.
The WRMA is primarily tasked with development of guidelines and procedures for allocating water, water monitoring, issuing and enforcing permitting, protecting water quality, collecting and processing data. The Act goes on to specify the process through which the WRMA should develop a national strategy to manage, protect, use, develop, conserve, and control the water. Plans should be specific to each catchment area with stated goals. A groundwater conservation area can also be created in areas when there is a need to protect public or commercial water supply. The role of non-governmental entities and community groups (called water resources user associations) were greatly enhanced by the Act, but final decision making continues to be centralized.

The WRMA has the ability to grant a permit and ensure compliance with the requirements. They shall first give an authorization to construct the borehole or well. Additional regulations regarding the licenses for water providers were detailed in the Water (services regulatory) rules. Unfortunately, permits are often issued without a good understanding of the aquifer or the impacts pumping would have on it.

The 2002 Act was updated again by the 2016 Water Act. This Act provides for the regulation, management and development of water resources and water and sewerage services in line with Kenya's new Constitution promulgated in 2010, which declares that access to clean and safe water is

Table 3-1 Hierarchy of Kenya's water institutions (adapted from World Bank, 2016)

Kenya Water Agencies Roles and Responsbilities			
National Level	Regulation and Dissemination	Infrastructure	
	Ministry of Water, Sanitation and Irrigation (WRA)		Policy Creation
Regional Level	Basin Water Resources Committe (BWRC)	Water Servies Regulatory Board (WASREB)	Regulatory Implementation
Local Level	Water Resources User Associations (WRUAs)	Water Service Providers (WSPs)	Direct Services
	Water Consumers and End Users		End User

a human right and tasks several counties with providing it, vesting the authority to manage water in those counties. The Act recognizes a shared responsibility between the national government and the county government and gives use of water for domestic purposes priority over irrigation and other uses. The Water Act continues to separate water resource management duties from water and sewage services. The Act created several new entities and redefined the roles of existing departments at national, regional and local levels.

On the resources side, the Water Resources Authority (WRA), formerly the Water Resources Management Authority, is focused on creating policies to protect, conserve, control and regulate use of water resources through the establishment of a national water resource strategy. The Basin Water Resource Committees (BWRC) are local catchment stakeholder groups under the WRA, which provides regional, transparent planning. At the lowest local level, the Water Resources Users Association (WRUA) manages the water for the community.

The Cabinet Secretary is obligated to create or revise a National Water Resource Strategy every five years with public participation. The goal of this strategy is “to provide the Government’s plans and programs for the protection, conservation, control and management of water resources” (Kenya Water Act, Section 10(2), 2016). Groundwater is not specifically listed in the description of the strategy; however, it is likely included in some of the catch-all language. Further, Article 23 recognizes that the Cabinet Secretary may need to make special measures to conserve groundwater in the public interest to preserve water supply for the public or industry or to protect the aquifer. For policy implementation, Article 56 states that groundwater abstraction is dictated by the Fourth Schedule of the 2010 Constitution, which defines the distribution of functions between the national and county governments. While permitting is a national obligation, counties are responsible authorities for the “implementation of specific national government policies on natural resources and environmental conservation, including…water conservation” and water services (Constitution of Kenya, Fourth Schedule, Art. 56, 2010).

As a result of these laws, Kenya has completed a National Water Master Plan 2030. This report is part of the larger Kenya Vision 2030 published in 2007, which includes water targets and references to the 1999 water policy. This water master plan includes national water policy and development targets and attempts to estimate sustainable groundwater yield for several catchment areas. Unfortunately, the plan ignores surface water/groundwater interaction and assumes uniformity across aquifers. It is highly unlikely that all aquifers would have comparable sustainable yields as recharge is highly variable across climates and lithologies. Additional data would provide greater accuracy.

Much of Kenya’s groundwater is shared with other countries, which compounds management challenges.
At least five significant transboundary aquifer groups are shared with neighboring countries: the Rift Valley aquifers, the Elgon aquifer, the Merti aquifer, the Kilimanjaro aquifer, and the Coastal sedimentary aquifers. Despite the amount of shared water, no cooperative use or protection agreements are in place.

3.1.4. Governance Challenges

Reviewing the situation in Kenya, several key challenges to effective groundwater management emerge. The first challenges are the current socioeconomic and conflict conditions throughout the country. Population is quickly increasing and much of the current population still does not have access to water. Groundwater development will be strongly tied to both of these issues.

> *“Perhaps the largest challenge is lack of capacity including staff, technical, and financial resources”*

Climate variability and predicted climate change uncertainties are currently not included in groundwater development decisions. Managing withdrawals towards sustainability (or any other target) requires considering the likelihood of longer droughts and heavier rainfall events. To do this effectively, one must first have knowledge of the resources involved. Critical scientific information related to recharge rates and connection to surface water needs to be understood in the context of a changing climate.

Perhaps the largest challenge is lack of capacity including staff, technical, and financial resources. “There is inadequate capacity in the WRMA offices responsible for the NAS. Between them—two geologists are deployed to Nairobi [sub-regional office] SRO, none in Kiambu SROs—groundwater staff must manage about 4,000 groundwater permits” (Mumma, 2007).

Lack of capacity often leads to lack of enforcement, which places the aquifer at the mercy of the commons. Common pool management of the resource negates interest in groundwater conservation. Implemented legal systems that include authorization protocols such as permits and water charges tend to improve compliance with larger goals. Currently, Kenya has moved away from centralized enforcement to a more localized approach utilizing aquifer-specific management plans and stakeholder/public participation. While this is a preferable governance structure due to the local character of water resources and demand, it is not effective without implementation support and consistent enforcement.

3.2. Jordan Case Study

3.2.1. Local Conditions

The Hashemite Kingdom of Jordan is a parliamentary constitutional monarchy made up of twelve governorates and ruled by King Abdallah II. As a small, largely desert, landlocked economy, Jordan has a relatively free market economy that depends on trade. Two-thirds of the economy is based on services, with the food industry and tourism being important contributors. Jordan is classed by the World Bank as an upper middle income country and plays an important geo-political role at the center of the Middle East. In particular, Jordan has absorbed waves of people displaced by conflict in the Palestinian territories, Iraq and Syria. Of Jordan's roughly 10 million people, some 2.4 million are classified as refugees by the World Bank.

3.2.2. The Water Context in Jordan

As an arid country with limited surface water, Jordan is heavily dependent on groundwater. Jordan suffers from both water shortage, with a very low availability of water per capita, and from water stress, with water usage exceeding the renewable supply. Jordan's efforts to address water scarcity are tied to the country's unique geography, as well as regional hydro geopolitics, the vast majority of the population and economic activity is situated in northwest Jordan, along with most of the surface and groundwater sources. Northwest Jordan is divided into a lowland and a highland portion, with the agricultural Jordan River Valley making up the former and the larger cities of Amman, Irbid and Jerash sitting atop the plateau that extends into eastern Jordan. The Jordan River and its tributaries provide the bulk of Jordan's freshwater supply, water that historically was used by the Jordan Valley Authority to supply a narrow corridor of irrigated farms stretching from the Syrian border south to the Dead Sea.

In Jordan, groundwater use and surface water use are tightly connected as the country strives to use and reuse its limited water supply. The Jordan Valley Authority's water supply is gradually being transitioned from freshwater to treated wastewater from the highlands. The highlands, home to most of the industry and population of the country rely heavily on groundwater extraction for water supply. Thus, the country is effectively turning groundwater pumped in the highlands for municipal and industrial (M&I) purposes into treated wastewater for irrigation in the lowlands. As urban demand grew and as the input of freshwater to the system was reduced by Syria and Israel, the wastewater systems were put in place for Amman's effluent, later to be follow for other cities located to the north. As wastewater replaces surface water in the Jordan Valley, the freed-up surface water is to be pumped up to the highland for M&I purposes, relieving the pressure on the groundwater resource.

Further to the east in the highlands, in the more sparsely populated Azraq and Mafraq governorates, large quantities of groundwater are used for irrigation, as well as for M&I purposes. This water usage is not connected to that in the western highlands and groundwater not consumed by crops is lost to evaporation or percolates into the groundwater table. Climate change in Jordan is bringing with it higher temperatures, less precipitation and more intense bouts of precipitation. The implication of these changes in such arid areas is that a larger portion of the annual water budget will go to satisfying atmospheric demand, i.e. as evapotranspiration. Thus, it is expected that groundwater recharge rates in the highlands will decrease, even as the incidence of flooding increases.

3.2.3. Groundwater in Jordan

There are eleven aquifers in Jordan, of which a few play a major role in the country's water supply (JMWI, 2018a) The A7/B2 aquifer with outcrops in the heavily populated northwest region makes up one-quarter of groundwater usage. A highly productive aquifer with pumping depths on the order of 50 to 250 meters, this aquifer provides high quality water. However, due to the intensity of use the aquifer is declining at rates of 1 to 12 m/yr with the highest declines in the area of Irbid and Mafraq near the Yarmouk River (JMWI, 2018a).

The Alluvium aquifer in the Jordan Valley and the Basalt and B4/B5 aquifers in the Azraq basin are relatively more shallow (5 to 150 m) and heavily used for urban centers, Syrian refugee camps and commercial groundwater irrigation.
These aquifers are declining at rates from 1 m/yr to 5 m/yr with the highest rates of decline noted in the Jordan Valley (JMWI, 2018a). In Azraq, groundwater temperature and salinity are also increasing and a shallow wetland has dried up, indicative of the declining water table. The Ram Aquifer, primarily located in Saudi Arabia, has been tapped for some 20% of the country's water supply with this water being pumped all the way to Amman. The Disi Aquifer, shared with Saudi Arabia, has very low recharge rates and is considered as non-renewable. Jordan pumps Disi water all the way to Amman for M&I purposes. This aquifer is declining at rates of from 0.6 to 5 m/yr (JMWI, 2018a).

Analysis by both the Ministry of Water and Irrigation and the USGS conclude that for basins with large withdrawals, the trend is towards increasing declines and worsening water quality (JMWI, 2018a, Goode *et al*., 2013). The United States Geological Survey (USGS) forecasts a decline in saturated aquifer thickness in the principal basins of about 30-40%, and falling to zero (i.e. no water available) in 5% of the locations by 2030 (Goode *et al*., 2013). As water levels fall, an increase in total dissolved solids and worsening of water quality in these aquifers is also observed (Al-Karablieh & Salman, 2016, Goode *et al*., 2013). Economic analysis for a number of key agricultural basins forecasts that these declines will lead to increasing costs of accessing groundwater for irrigation, rendering many of the low value crops unviable in ten to thirty years, crops that account for a large proportion of current area planted in these basins (Rosenberg & Peralta, 2012).

3.2.4. The Groundwater Management Challenge in Jordan

Jordan has 710 million m³ of renewable water supplies, of which 40% is the groundwater safe yield, 30% is the Jordan River freshwater and the remainder is treated wastewater, local surface water and desalinated sea water (JMWI, 2018b). An additional 143 million m³/yr are estimated to be available from nonrenewable groundwater for fifty years, for a total time-limited sustainable supply of 853 million m³/yr.

In 2017, the demand for water in Jordan was 1,412 million m³ and the amount actually used, once shortfalls are taken into account, was 1,047 million m³. This amount does not include 225 million m³ of undocumented pumping from wells without permits, first documented in 2014 (Al-Karablieh & Salman, 2016). Comparing water use in 2017 with that in 2000, the observed increase is 30% with a compounded annual growth of 1.5% (JMWI, 2018a; 2018b). This growth incorporates the water deployed to meet the influx of refugees since 2011.

> *"As the surface water resource in Jordan is fully used and a significant portion of the groundwater is used twice, first for M&I and second as wastewater for irrigation"*

As the surface water resource in Jordan is fully used and a significant portion of the groundwater is used twice, first for M&I and second as wastewater for irrigation, the deficit in renewable supply is made up from groundwater. Nationally, groundwater depletion is 22% of total usage if the drawdown of non-renewable groundwater is excluded. If mining of this fossil water is included, the depletion amount rises to 36% of total use (or 379 million m³/yr). However, even these sums are based on the official records of water usage, which does not take into account the aforementioned undocumented and illegal water use of approximately 225 million m³. Therefore the total unsustainable groundwater extraction may be on the order of 600 million m³/year, representing 60% of the official usage or 220% of the country's safe yield for groundwater.

Of further concern is that the draw on groundwater continues to grow. From 2000 to 2017, M&I water use grew by 69% or an annual rate of 3%. In theory, this allows for the production of higher amounts of wastewater for irrigation, which will eventually result in the pumping of surface water supplies to the highlands to alleviate this draw on groundwater. This shift is underway, but it is unclear if it will be sufficient as long as water use increases at such a rapid pace in the highlands.

3.2.5. Current Groundwater Governance

Jordan's legal regime to manage water is dictated by three sources: The Water Authority of Jordan (WAJ) law 18 of 1988, the Jordan Valley Authority (JVA) law 30 of 2001, and the Ministry of Water and Irrigation (MWI) law 54 of 1992.
In Jordan, all water resources are considered property of the State and are not able to be used or transferred outside of limited legal parameters, although there are exceptions for domestic water needs. Although water is not owned by individuals, private water use rights can be obtained. Criminal and financial penalties can result if a non-authorized groundwater well is drilled.

The MWI is the governmental agency tasked with creating water strategy, policy and planning. It was created to pursue a more integrated approach to national water management throughout the country. "MWI aims to upgrade, develop and regulate the water sector and enhance the quality of water services" (Centre for Environmental Research, 2020).
In addition to planning, implementing and overseeing a national water strategy, it is also tasked with executing international water agreements and developing private sector partnerships with support from international donor organizations.

Two agencies report to the MWI. The WAJ is the direct services provider tasked with planning, construction, operation and maintenance of water and wastewater systems. The second institution directly subordinate to the MWI is the Performance Monitoring Unit (PMU), which manages private sector participation projects.

To meet its obligations as service provider, the WAJ is tasked with mapping water resources, developing policies to provide water to citizens; preventing pollution of water resources; and regulating the uses of water, preventing waste, and conserving water. WAJ sets policy for use and management of resources through a board chaired by the Minister of MWI and including the Secretary Generals of JVA, ministries of Planning, Agriculture, Municipal and Rural Affairs, Environment, Health, Industry & Trade, Finance, Energy and Natural Resources and an expert member.

The MWI/WAJ grants for drilling licenses and abstraction permits in accordance with the effective groundwater legislation (Al-Karableih & Salman, 2016). Tariffs are placed on all wells, calculated based on volume of water use; however, this system has been criticized for lack of enforcement and as being too inexpensive. A survey of farmers in the JVA disclosed that billing efficiency was only 82% and collection efficiency only 75% (van den Berg & Al Nimer, 2016). Despite this allowance, many illegal wells remain (Al-Karableih & Salman, 2016).

The Jordan Valley Development Law of 1988 established the JVA to manage the socio-economic development of the Jordan Rift Valley. The JVA accomplishes this by studying the resources, planning and building projects, continued operation and maintenance of irrigation projects and monitoring of public and private wells in the region. Specifically, they are mandated to plan, design, construct, operate and maintain irrigation projects, dams and hydroelectric power stations in the region. In 2011, the national government realized the challenges of a fully centralized groundwater management approach. To disperse some of the responsibility for municipal water supply, three additional utility companies were created to assume a more localized responsibility to distribute water through the authority of the WAJ (Al-Karableih & Salman, 2016).

Groundwater policy is centralized in the National Water Strategy 2016-2025, the 2016 Groundwater Sustainability Policy, and the Irrigation Water Policy. The Groundwater Sustainability Policy was released by the Minister of Water and Irrigation as part of a suite of policies related to the National Water Strategy (JMWI Groundwater Sustainability Policy, 2016). In the policy, the importance of groundwater and the significant over abstraction in the country are noted. The goal of the policy is to effectively manage these scarce resources. The document includes a list of policy benchmarks and assumptions about groundwater by which implementation decisions should be guided.

Many of the policies are value driven to ensure that water used is going to its highest value use. For example, the water strategy states that agriculture should reduce its demand on water to allow for a higher value use, such as M&I, to have access. There is also the opportunity for funding and incentives for agricultural projects that increase efficiency resulting in reduced abstraction. The use of appropriately-treated wastewater is encouraged as is development of groundwater models for regional aquifers. Finally, it calls for a comprehensive groundwater basin management plan to be included in the National Water Master Plan and all legislation to be strictly enforced against all users acting in contravention of the rules.

The document also states principles upon which all policies should be shaped. These include an understanding of the importance of groundwater as a resource in Jordan and the need to use it efficiently. The adoption of Integrated Water Resources Management (IWRM) to ensure management based on principles of sustainable use, economic efficiency and social equity is a goal. As part of this, there is a stated objective of managing groundwater in relationship to surface water, incorporating climate change adaptation, and developing new water sources through desalination, wastewater treatment, water harvesting, improved aquifer storage and recovery, as well as enhanced recharge.

Stakeholder participation can educate users, particularly farmers, as well as focus on data needs and collection. Current data systems should be closely monitored and additional data sets should be included. A comprehensive national water data bank could be managed by MWI. As in Kenya, comprehensive data sets are a challenge as many water resources are not well studied.

Like Kenya, Jordan has internationally shared groundwater; however, more efforts have been made to collaboratively manage these for the good of both countries. The 2016 National Water Strategy commits Jordan to cooperating with neighboring nations and jointly managing shared aquifers. Some evidence of this in practice can be found in the Disi Aquifer, shared with Saudi Arabia, which is a fossil water aquifer that is being significantly dewatered in some areas. The estimated withdrawal of 1,000 million cubic meters (MCM) of groundwater per year near the Saudi Arabian town of Tabuk created a large cone of depression, which affects many wells (Müller *et al*., 2017). In April 2015, the two counties entered into an agreement for the Management and Utilization of the Ground Waters in the Al-Sag/Al-Disi Layer focused on the protection and management of the system.

3.2.6. Governance Challenges

Due to its strategic national importance, Jordan has focused policy attention on a framework for groundwater management and protection. However, challenges remain in ensuring that the desired outcomes become a reality. Despite the agencies appointed to manage water in Jordan, there is still no dedicated manager of groundwater. In addition, jurisdictional overlaps exist between the WAJ and WMI. Exemplified by irrigation as a major use of water, which is managed through the Minister of Agriculture, increased inter-governmental coordination is also needed.

Further, other than the JVA, there are no smaller, regional authorities managing the aquifers. Lack of local implementation and oversight limits stakeholder management and education of the end user.
Central to Jordan's goals is partnering with users and stakeholders throughout the nation, and outside for shared resources. In particular, the education of agricultural stakeholders is critical. There is still a need for widespread involvement of farmers in order to meet the stated goals.

Similar to Kenya, there is a gap between written policies and clear, consistent implementation. Laws are needed to better define what use rights are available, for which purposes and how they can be accessed. Permitting rules need to be developed and implemented consistently for all users.

On the funding and incentive side, there are few tools in place to meet stated goals, such as moving water to higher value uses and reducing water used by agriculture. Tools created for this purpose, such as tariffs, need to be used consistently to achieve desired results. Financial shortfalls often inhibit progress. More funding needs to be available to pursue projects such as incentivizing efficient irrigation technologies, or preparing wastewater for reuse. Further, although the policies state that a goal is to reduce groundwater use for agriculture, water pumping is still heavily subsidized through inexpensive pricing and lack of fee collection.

04

Best Practices for Groundwater Governance

4.1. Policy Frameworks: Regulation, Implementation and Oversight

The increasing reliance on groundwater to meet the needs of growing populations, coupled with the risks of over-abstraction, necessitates proactive management of aquifers. In many cases, water laws and implementing authorities have historically focused on surface water with little specialized attention to the groundwater resource, either on its own or as it interacts with surface waters; however, integrated water management that provides climate change resiliency cannot happen without the inclusion of groundwater. Degradation associated with common-pool resources is likely without concerted legal and managerial oversight.

There are many ways to structure these systems, but some considerations should be present to maximize outcomes. Much has been written about groundwater governance and among the recommendations several aspects are consistent (Megdal, 2018). Common elements include: the use of science and data; functioning and effective governmental authorities; a clear legal framework; the need for public participation; and, sufficient funding to support programming. Many of these goals can be challenging in countries with restricted public budgets, protracted crises, or struggles with corruption. In these contexts, attaining so-called "good" governance is difficult if not impossible; actual practices should be adapted to the local situation and local capacities.

Although water resources have regional considerations, clear goals regarding groundwater should be set and committed to at the national level. These can include selecting from broad policy objectives such as the technical and/or economic efficiency of resource use, equitable access through moving water to underserved or disadvantaged sectors, or protecting the environment through limiting drawdown and safeguarding groundwater quality, or, providing widespread access to water on a first-come first-served market basis. A good example of framing a national vision can be seen in Jordan's Groundwater Sustainability Strategy. While many of the goals listed in that document could be considered general, there is a clear goal to ensure that water is going to new users by ensuring efficient use of water in more traditional sectors.

While Kenya has a vision for water access driven by the 2010 constitution, it does not have a detailed policy framework to guide management of groundwater. Kenya has not faced the challenge of over abstraction seen in Jordan. Jordan's dependence on groundwater coupled with the need to free up water to meet new demands encourages efforts to address illegal withdrawals and cascade the use of groundwater from urban uses in the highlands to treated wastewater use in irrigation in the lowlands. Countries, like Kenya, that have not yet experienced overdrafting, have the opportunity to establish goals and mechanisms for managing groundwater before issues arise.

Generalized outcomes can be specified as national policy; however, detailed regulations and management are needed to reflect local physical and economic circumstances. For example, management criteria for a non-recharging aquifer will differ significantly from a quickly recharging water source. Local authorities, on an aquifer or sub-aquifer scale, should be empowered to interpret and apply the national vision to their areas. Local management also has the facility to coordinate with related sectors, such as agriculture or municipal, and can lead to a multi- sectoral approach.

With the exception of the JVA, which manages surface water for irrigation, Jordan has maintained water policy at the national level. Due to the challenges of over-abstraction already present, local management could focus on obtainable goals for given aquifers and their recharge basins. While Kenya recently moved away from the national-only model by creating counties and promulgating regulations that delegate authority to local groups, sufficient support has not been provided to render the management measures effective. Many offices have very limited human capacity or funding to effectively administer the resource and implement regulations. Financial investments should be aligned with the stated outcomes. Without sufficient support, even the best written policies cannot be effected.

Decentralization can be very effective for implementation but, typically, it will only be partial. There are many authorities, functions and roles that need to be carried out to govern and manage groundwater successfully. Which of these are held by the central government and which are delegated can vary. Typically the trade-off will be between satisfying the central government's desire for control and the regions' desire for autonomy.

Crafting a system that allows elements of subsidiarity is generally advised with a local and common resource like groundwater. Certain functions though –particularly the scientific and technical elements – may most efficiently be provided from the center. Pitfalls to vesting authority and functions locally certainly exist as well. Regional actors may be more susceptible to corruption or selective enforcement and local administrators may also be impacted by political shifts. To ensure trust, expectations of consistent and transparent management should be set and overseen by the federal or national authority to which the regional groups report. In fragile contexts, the need for oversight may be considerable. Given the top-down nature of traditional engineering approaches to water infrastructure and management, the challenge in these countries is likely to be to open up venues for local participation in planning and decision-making, which allows for administrative decentralization as regional capacity and appetite evolves.

Government entities should involve local stakeholders at all levels. Public, private and civil society actors should be involved in developing and implementing localized goals, implementation and data sharing. Education will be an important factor for success. Local users need to understand the laws as well as basics about the groundwater system and its relationship to surface water and land use challenges. This is particularly important in pastoral communities, as seen in northern Kenya, where common pool damage of land resources is prevalent. With attention paid to governmental structure, clear policy initiatives and involvement of affected parties, local management of policies that represents a range of users and their objectives can be developed.

For any of the management structures outlined above, several overarching considerations need to be included in the creation and implementation of groundwater rules. Perhaps the most important of these is science. One of the biggest challenges to effective management is lack of understanding. The invisible nature of groundwater resources poses the largest challenge to its protection. Lack of scientific and technical knowledge challenges proper governance.

Achieving sustainability first requires a sufficient understanding of the system's features including recharge, transmissivity, storage and extent. Without a full understanding of the subsurface dynamics, an issue may not be discovered until there is a crisis such as reduced well yield or a communal health problem, at which point mitigation options are more limited. Lack of financial capacity exacerbates the inability to collect data to measure and monitor the resource; therefore, crowd sourcing of data collection and utilizing information collected from diverse partners including NGOs diversifies information available.

Understanding the resource not only guides withdrawals to avoid unintended consequences, it can also be used to develop innovative systems to assist the natural environmental processes. A good knowledge of an aquifer's recharge system can pave the way for protection of sensitive areas as well as the development of enhanced recharge projects. The ability to view groundwater as part of a system also allows for the integration of projected climate change impacts.

In addition to understanding the relationship of surface water to groundwater, water must also be considered as part of the land use protocols. There is a direct relationship between land management and water resources. This can clearly be seen in Kenya, where pastoral lands often reflect land degradation caused by overgrazing. The land compaction coupled with minimized vegetation increases the volume of run off and prevents seepage into aquifers. Overland flow of precipitation that reaches surface water bodies often has more sediment load compared to water flowing across lands with heavy grass cover.

4.2. Local Strategies for Groundwater Management in Fragile Contexts

As alluded to in the prior sub-section, having an agreed-upon objective for groundwater use and management, along with the laws, regulations and administrative capacity to implement such, is essential to good governance of groundwater. And yet, in countries with low levels of development, ongoing conflict and recurrent humanitarian crises – as well as low levels of administrative capacity and most likely limited citizen-state relations – the likelihood that the state is going to reach out and govern groundwater in rural areas strains credulity. Jordan provides an example here, as even with a demonstrated need for good management and in the presence of an ambitious set of water policies and considerable centralized capacity, the existence of un-accounted groundwater use totaling over one-fifth of all water use in the country went unreported and un-addressed for many years. Perhaps, had involvement in groundwater governance been devolved to the governorate or to basin authorities, this might not have persisted for so long. But even in Kenya, a relatively prosperous and well-governed country in SSA, where certain functions have been devolved to the county level, there is little known about the state of the groundwater resource. This is not surprising as Kenya has yet to develop it. To expect Kenya to have a functioning system for administering groundwater seems unlikely. The difficulty with groundwater is that waiting to implement governance and management until the resource is already on its way to exhaustion means it will likely be hard to manage its decline, or stave off decline, if that is the objective.

As the saying goes, "you can't manage what you can't measure". This section flips the question from what can centralized authorities do to successfully govern a local resource to the question of what needs to be done at the local level to enable successful governance. Principally, this task involves understanding existing resource use and tenure arrangements associated with this use. Developing this set of information is an activity that international NGOs (INGOs) and their local development partners are ideally situated to perform, given their involvement in communities and their participation in the provision of water supply, sanitation and hygiene (WASH) in communities and camps. Of course, any voluntary effort directed at gathering, compiling and making such information publicly available will be partial in nature and faces myriad challenges (Thomson *et al.*, 2012). Given advances in information technology and the increased use of crowdsourcing for developing detailed raw data for later aggregation, a central task is to ensure that there are standards for collecting, recording and uploading data.

A simple first step is to geolocate existing wells and boreholes. This may be easier for boreholes if drilling permits are required by the state and records are kept. For example, in Mali the national directorate maintains a data set of more than 16,000 boreholes throughout the country. Information recorded includes the coordinates, whether water was found, depth of water, yield of the well and water quality (Díaz-

Alcaide *et al*., 2017). Documenting boreholes is probably a first priority as they are likely to serve larger users and thus represent a large portion of water usage. But in many less well-off areas where groundwater is relatively close to the surface, hand dug wells for human or livestock use may be the rule. For example, in one village in central Mali, a total of 57 wells serve the needs of a community of 1,500. Knowing where these are – given that rural households will be largely dependent on these wells – may not be that important in terms of understanding total withdrawals, but may be very important in terms of protecting these households as larger, commercial uses of groundwater are developed.

Once wells are located, a range of information can be collected and associated with these points on the map. Basic information simply replicates the information that would be required on an official permit to use water (Aylward *et al*., 2016). This information includes the name of the person, household or community that controls access to the water source and is responsible for its upkeep (nominally the well/borehole "owner"). Other basic parameters surrounding use of the source include:

- the amounts of withdrawal specified as one or more of the following:
  - a maximum instantaneous flow withdrawal rate;
  - a total volume per year; and
  - for irrigation, a volume per unit area per year
- the period of the year during which the withdrawal occurs or a 'season' of use;
- the type of use (e.g., domestic, irrigation, commercial);
- the place of use (i.e., the fields on which irrigation water will be used, or the community service area)
- for irrigation, the extent of use in terms of the area to be irrigated (e.g., in acres).

Of course if there are multiple uses and users of a given well/borehole then this information would ideally be collected for each. It may also be useful to define the maximum use that would be made by users for each use, as this amount would be the amount for which a user would need an official permit. Due to seasonality, this maximum amount is not necessarily equivalent to the total amount used and, thus, actual measurements of water extracted is another useful set of annualized data. For boreholes, meters measuring and aggregating flow rates are ideal, but are not often installed or functioning properly. An alternative or supplemental method is to record the energy consumed in pumping and convert this using an established power/flow curve for the pump.
For hand pump systems or open wells from which water is extracted manually, approximations will be needed including of typical use during wet/dry season days and/or of estimated uses based on household numbers and outdoor area irrigated in the dry season. Of particular interest in rural, dryland settings will be how the use (including yield of the source) and water quality vary from dry to wet season.

Beyond these fundamental data points is additional information about the behavior of the groundwater source, which would come from:

- estimating peak yields from the source, for dry and wet seasons and at the end of drought years and wet years;
- tracking of the water level in the well to obtain an understanding of its diurnal fluctuation in both dry and wet seasons; and
- documenting periods of time when the yield is overwhelmed by demand and whether the shortfall is made up elsewhere and from which sources.

With respect to well function and the local hydrogeology, further steps are to document clusters of wells/boreholes and assess how they perform over similar time frames.
A key question to examine is whether the use of nearby wells impairs yield and/or water levels at peak use during the dry season.

With respect to permits and tenure for the water source, the working assumption is that the sources are unlikely to be required to register for a permit due to a lack of permitting regulations or due to exemptions for small-scale household or livestock uses. If a permit is required then the information collected above can be used to register the water source. Regardless, a primary concern in terms of establishing the right to access and use groundwater will be the status of customary rights to water in the country. Efforts are under way to better understand water tenure and document the extent of these rights across developing countries (Hodgson, 2016, RRI & ELI, 2019). Documentation of customary uses is therefore another potentially useful preparatory step towards effective groundwater governance. Information that may be gathered includes answers to the following questions:

- When were the wells/boreholes constructed and in what year were they first used?
- What changes in tenure have occurred over time, documenting the chain of tenure back to construction and first use?
- What changes in access, usage and type of usage have occurred over time?
- Is there a priority order for the use of the water source or rules for how the burden of shortage is shared/distributed among users or uses?

This type of tenure information is just an entry point to documenting how rights of access, use, exclusion, transfer and management are, or are not, specified for this water source, or for groups of water sources that locals understand as tapping in to the same aquifer.

In fragile countries, policy reform and putting in place the building blocks of good governance (generally, but specifically for groundwater) is a necessary but not sufficient condition for success. Policies, laws and regulations need to be implemented to have effect and this can be very difficult in fragile contexts. This second section, therefore attempts to identify proactive steps that communities and local officials, supported by INGOs and local development partners, may take to prepare for active governance of the resource. While these are practical and unexciting tasks, the reality is that there is nothing glamorous about the laborious process of

achieving good governance and water management. However, if this work is not done and the information not available, then the risk faced by communities is magnified when officials arrive from the capital with laws and regulations in hand, or when the resource starts to dwindle in the face of overwhelming and growing demand.
Further, such efforts can be used as a way to increase communities' technical understanding of an invisible resource and to build their internal capacity to measure, monitor and manage groundwater.

> *"A proactive effort by communities and local government, and supported by INGOs, to gather, compile and share data on groundwater use"*

05
Conclusions

The need for social and economic development and the difficulty of making headway on this challenge appears worse in 2020 than it has been for many decades.
Even before the COVID-19 global pandemic, there was an increase in the occurrence of armed conflict and natural disasters in countries already lagging in development and self-governance indicators.

For water professionals and those addressing the risks and opportunities associated with groundwater resources and their usage, these developments make an already difficult job even more so. Persuading governments, the private sector and communities to adopt forward-looking regulations and management practices for an invisible, common pool resource before it is too late has always been a vexing task.

The review and analysis in this paper suggest that there is reason to cheer in that some of the more advanced and progressive countries in this cohort of conflict and fragile countries – in this case Kenya and Jordan – do have sensible policies, laws and regulations in place. Still, the dedication of sufficient resources to, and participation of civil society in, planning, implementation and enforcement of existing governance frameworks remains a challenge for these countries. Meanwhile, away from capital cities in communities that are often outside the grasp of formal government structures and processes, there is an opportunity to pursue another avenue to advance the cause. A proactive effort by communities and local government, and supported by INGOs, to gather, compile and share data on groundwater use and tenure systems would help prepare for the day when governance is critical in terms of allocating and managing supplies and when countries are strong enough to engage with regions on groundwater governance. For INGOs, merely drilling boreholes is not enough. Much can be done to raise community awareness and capacity to manage groundwater, while at the same time promoting effective and equitable access to this critical resource.

References

Al-Karablieh, E. & Salman, A. (2016). Water Resources, Use and Management in Jordan - A Focus on Groundwater. Groundwater Governance in the Arab World. International Water Management Institute. (accessed 4 August 2020).

Aylward, B. (2016). Water, Public Goods and Market Failure. Political Economy of Water Markets. AMP Insights and Ecosystem Economics. Portland, p. 23.

Aylward, B., Pilz, D. & Sanchez, L. (2016). Political Economy of Water Markets in the Western United States. Political Economy of Water Markets. AMP Insights and Ecosystem Economics. Portland, p. 94.

Aylward, B., Popp, C. & Burchi, S. (2009). Water Resource Quantity: Allocation and Management. In Vapnek, J., Aylward, B., Popp, C. & Bartram, J. (eds.) *Law for Water Management: A Guide to Concepts and Effective Approaches*, FAO. Rome.

van den Berg, C. & Al Nimer, S. (2016). The Cost of Irrigation Water in the Jordan Valley. The World Bank. Washington, D.C.

Blandenier, L., Burt, M., Milnes, E., Brunner, P. & Perrochet, P. (2016). The Merti aquifer (Kenya), a sustainable water resource for the Dadaab refugee camps and local communities? Kumasi, Ghana: 6.

Centre for Environmental Research. (2020). Ministry of Water & Irrigation. Available at https://www.ufz.de/nice-jordan/index.php?en=43436#:~:text=Ministry%20of%20Water%20and%20Irrigation&text=MWI%20is%20responsible%20for%20overall,coordination%20with%20WAJ%20and%20JVA (accessed 6 October 2020).

Chen. C., Noble, C., Hellmann, J., Murillo, M. & Chawla, N. (2015). University of Notre Dame Global Adaptation Index: Country index Technical Report. Notre Dame. South Bend.

Constitution of Kenya, Fourth Schedule, Art. 56. (2010).

CRED & UNISDR P. (n/d). Economic Losses, Poverty & Disasters: 1998-2017. Centre for Research on the Epidemiology of Disasters and United Nations for Disaster Risk Reduction.

Díaz-Alcaide, S., Martínez-Santos, P. & Villarroya, F. (2017). A Commune-Level Groundwater Potential Map for the Republic of Mali. *Water*. 9(11), p. 839.

Goode, D. J., Senior, L. A., Subah, A. & Jaber, A. (2013). Groundwater-Level Trends and Forecasts, and Salinity Trends, in the Azraq, Dead Sea, Hammad, Jordan Side Valleys, Yarmouk, and Zarqa Groundwater Basins, Jordan. No. Open-File Report 2013-1061. US Geological Survey. Reston, VA.

Hardin, G. (1968). The Tragedy of the Commons. *Science*, 162(3859), pp. 1243–1248.

Hodgson, S. (2016). Exploring the concept of water tenure. FAO. Rome, p. 94.

JMWI. (2018a). Water Year Book: Hydrological Year 2016-2017. Ministry of Water and Irrigation, Hashemite Kingdom of Jordan. Amman.

______. (2018b). Jordan Water Sector Facts and Figures 2017. Ministry of Water and Irrigation, Hashemite Kingdom of Jordan. Amman.

JMWI Groundwater Sustainability Policy. (2016). Available at http://extwprlegs1.fao.org/docs/pdf/jor159002E.pdf (accessed 12 August 2020).

Kenya Water Act, Section 10(2). (2016).

Kummu, M., Guillaume, J. H. A., de Moel, H., Eisner, S., Flörke, M., Porkka, M., Siebert, S., Veldkamp, T. I. E. & Ward, P. J. (2016). The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. Scientific Reports, 6(1), p. 38495.

Megdal, S. B. (2018). Invisible water: the importance of good groundwater governance and management. npj Clean Water, 1(1), p. 15.

Müller, M. F., Müller-Itten, M. C. & Gorelick, S. M. (2017). How Jordan and Saudi Arabia are avoiding a tragedy of the commons over shared groundwater. Water Resources Research, 53(7), pp. 5451–5468.

Mumma, A. (2007). Kenya's new water law: an analysis of the implications of Kenya's Water Act, 2002, for the rural poor. In Koppen, B. van., Giordano, M. & Butterworth, J. (eds.) Community-Based Water Law and Water Resource Management Reform in Developing Countries. CABI. Wallingford, pp. 158–172.

Mwango, F. K., Muhangu, B. C., Juma, C. O. & Githae, I. T. (2004). Groundwater Resources of Kenya. In Appelgren, B. (ed.) Managing Shared Aquifer Resources in Africa, Proceedings of the International Workshop Tripoli, Libya, 2-4 June 2002. UNESCO. Paris.

Ostrom, V. & Ostrom, E. (1972). Legal and Political Conditions of Water Resource Development. Land Economics, 48(1), pp. 1–14.

Petryniak, O., Proctor, K. & Kurtz, J. (2020). Towards Resilience: Advancing Collective Impact in Protracted Crises. Mercy Corps. Washington, D.C.

Pettersson, T. & Öberg, M. (2020). Organized violence, 1989–2019. *Journal of Peace Research*, 57(4), pp. 597–613.

Radar Technologies International. (2013). Advanced Survey of Groundwater Resources of Northern and Central Turkana County, Kenya: Final Technical Report. UNESDCO. Paris, 78.

Randall, A. (1983). The Problem of Market Failure. *Natural Resources Journal*, 23, pp. 131–148.

Reuters. (2018). Kenya takes a look into the unknown: Its underground water reserves. 2 July.

Rosenberg, D. E. & Peralta, R. (2012). Economic Impacts of Groundwater Drawdown in Jordan.

Institutional Support and Strengthening Program. US Agency for International Development. Amman.

RRI & ELI. (2019). Whose Water? A Comparative Analysis of National Laws and Regulations Recognizing Indigenous Peoples' and Local Communities' Rights to Freshwater. Rights and Resources Initiative and the Environmental Law Institue. Washington, D.C.

Schlager, E. & Ostrom, E. (1992). Property-Rights Regimes and Natural Resources: A Conceptual Analysis. *Land Economics*, 68(3), p. 249.

The Guardian. (2013). Terror in Nairobi: the full story behind al-Shabaab's mall attack. 4 October.

______. (2017). Two rangers shot dead in Kenya's Laikipia conservation area. 6 June.

Thomson, P., Hope, R. & Foster, T. (2012). Is silence golden? Of mobiles, monitoring, and rural water supplies. *Waterlines*, 31(4), pp. 280–292.

Thornton, N. (2010). Climate Change in Kenya: focus on children. United Nations Children's Fund United Kingdom. London, 31.

Transparency International. (2020). Results - 2019 - CPI. Available at https://www.transparency.org/en/cpi/2019/results (accessed 22 August 2020).

UNDP. (2018). Human Development Data (1990-2018) | Human Development Reports. Available at http://hdr.undp.org/en/data (accessed 27 July 2020).

WHO & UNICEF. (2019). Progress on Household Drinking Water, Sanitation and Hygiene, 2000-2017: Special Focus on Inequalities. United Nations Children's Fund (UNICEF) and World Health Organization (WHO).

World Bank. (2016). Understanding the Kenya 2016 Water Act. Available at https://www.2030wrg.org/wp-content/uploads/2016/12/Understanding-the-Kenyan-Water-Act-2016.pdf.

______. (2020). Country Policy and Institutional Assessment | DataBank. Available at https://databank.worldbank.org/source/country-policy-and-institutional-assessment (accessed 22 August 2020).

II

Tools for Management

4

Conservation, Protection, and Management of Urban Groundwater through City Master Plans: A Case of Indian Cities

Victor R. Shinde and Lovlesh Sharma

Victor R. Shinde, National Institute of Urban Affairs, New Delhi, India.
e-mail: vshinde@niua.org
Lovlesh Sharma, National Institute of Urban Affairs, New Delhi, India.
e-mail: lsharma@niua.org

Abstract

India is the largest user of groundwater in the world accounting for 25% of the global groundwater extraction. Indiscriminate abstraction and use over the years, invariably in urban areas, has led to a crisis where twenty major cities are expected to run out of groundwater in the near future. The World Bank warns that half of India's districts are threatened by groundwater depletion or contamination, and if current trends persist, 60 percent of India's districts are likely to see groundwater tables fall to critical levels within two decades. Other global cities in the world such as Bangkok, Jakarta, Mexico, Sana, Sao Palo, Istanbul, etc. are also facing similar challenges. There has, therefore, never been a better time to discuss and implement sustainable forms of groundwater management. This paper seeks to elaborate and focus on the use of city planning instruments—through Master Plans—for groundwater-sensitive planning and management. These instruments include Floor Area Ratio; Land Use Planning; Transferable Development Rights; Urban Design Elements; Norms and Regulations; Sectoral Strategy; Interlinking Blues and Greens; Special Projects; and Economic Instruments. The paper expounds on these using practical case studies from Master Plans of fifteen Indian cities—Andhra Capital Region, Bengaluru, Bhopal, Chandigarh, Chennai, Delhi, Gurgaon, Hyderabad, Jaipur, Kozhikode, Mumbai, Noida, Panaji, Puducherry, and Surat. Given that Indian cities are comprised of large brownfield areas, which is true for most other cities in the world as well, the paper also presents an analysis of the application of the planning instruments in both greenfield and brownfield areas. It is expected that this study will provide useful insights for planners and city officials from different parts of the world to scale up the use of planning instruments to conserve, protect and manage urban groundwater resources.

Keywords

Brownfield development, cities, development plan, greenfield development, india; master plan, sustainable groundwater management

01

Introduction

Groundwater is a major source of water in many of the world's cities, especially in Asia. India is the largest user of groundwater in the world accounting for 25% of the global groundwater extraction (World Bank, 2019). More than 60% of the country's irrigated agriculture and 85% of drinking water supplies are dependent on groundwater (World Bank, 2012). 50% of Indian cities rely on groundwater as the major source of supply. In light of the above, it became a major area of concern in the country when, in 2018, India's apex Planning Organization, NITI Aayog, published a Composite Water Management Index Report suggesting that twenty-one cities will run out of groundwater by 2020 (NITI Aayog, 2018). A year later, the World Bank (2019) warned that half of India's districts are threatened by groundwater depletion or contamination, and if current trends persist, 60% of India's districts are likely to see groundwater tables fall to critical levels within two decades.

> *"India is the largest user of groundwater in the world accounting for 25% of the global groundwater extraction. More than 60% of the country's irrigated agriculture and 85% of drinking water supplies are dependent on groundwater"*

The situation with groundwater reserves in the country has changed quite rapidly over the last few years. Figure 4-1 presents a picture of how the groundwater table depth across India has changed over just five years, from 2013 to 2018. It is quite evident that there has been an alarming depletion the groundwater resources across the country. If an imaginary line were to be drawn to bisect the country longitudinally, it is noteworthy that the depletion is far more serious in the western part that the eastern part. Interestingly, the western part is more urbanized and has greater economic development than its eastern counterpart. However, there is not much difference in the population between the two parts. While there are differences in geology, topography and general physical conditions between the two parts, this comparison to some extent accentuates the role of urban development in the exploitation of groundwater resources.

There has, therefore, never been a better time to discuss and implement.

The use of planning instruments in groundwater management is a relatively unexplored area in literature. Traditionally, the rich body of literature on urban groundwater has generally covered aspects related to assessing impacts of urban development on groundwater (e.g. Yar, 2000; Wakode *et al.*, 2018); groundwater recharge in urban aquifers (e.g. Mautner *et al.*, 2020; Patel *et al.*, 2020; Khan *et al.*, 2020; Ruiz, 2015; Adhikari *et al.*, 2020); practices for sustainable (e.g. Ahmad & Al-Ghouti 2020; Sayed *et al.*, 2020) and adaptive groundwater management (e.g. Thomann *et al.*, 2020); climate change impacts on groundwater (e.g. Ashwell *et al.*, 2018); groundwater remediation (e.g. Qian *et al.*, 2020); groundwater assessment (Abu-Bakr,

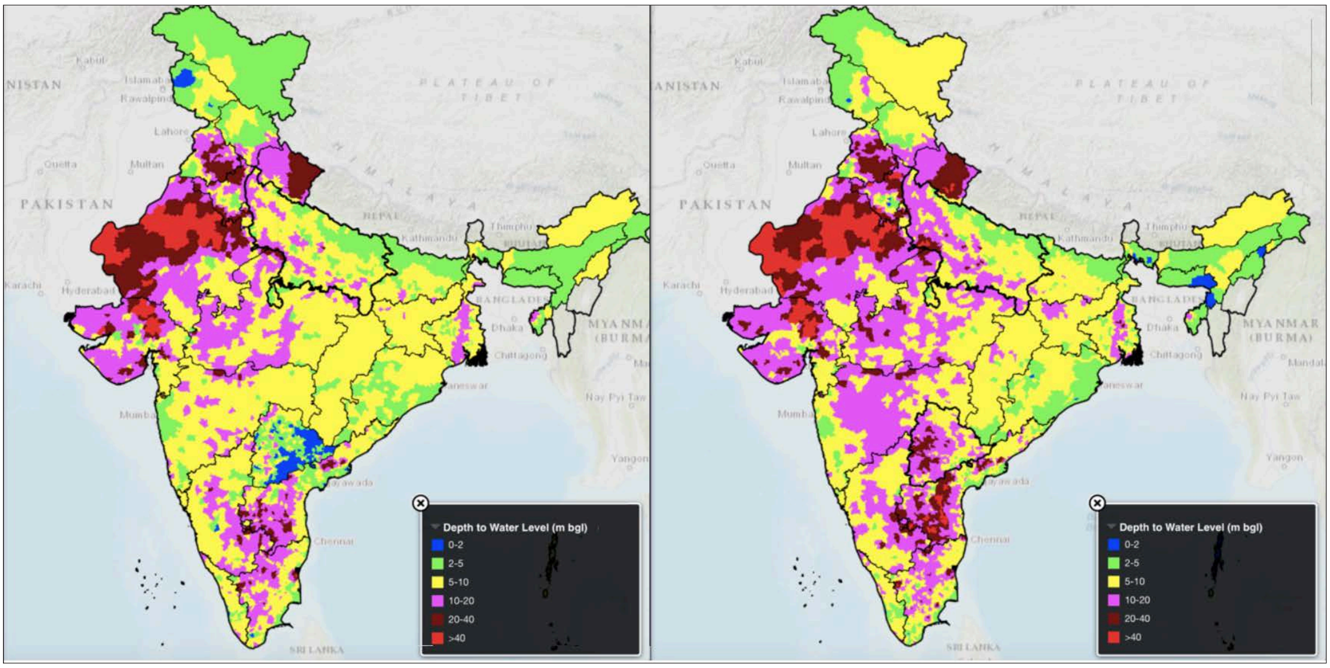


Figure 4-1 *Status of groundwater depletion from 2013 (left) to 2018 (right). (open source data from India WRIS (2020), Ministry of Jal Shakti, Govt. of India, Scale 1:50,000)*

2020); among others. The planning aspects of groundwater in literature are generally confined to sustainable use and yield (e.g. Abrishyamchi *et al.*, 2020); land-use planning (e.g. Lavoie *et al.*, 2013; Jiménez-Madrid *et al.*, 2017); and groundwater allocation models (Lalehzari & Kerachian, 2020). One of the earliest studies in this regard by Carmon *et al.* (1997) looked at water-sensitive urban planning with a view to protect groundwater. The recommendations, however, exclusively centered on recharging groundwater through urban design concepts that allowed groundwater to percolate in the ground.

All the aforementioned studies are very relevant studies and can certainly help in informing decision making on groundwater management. However, like any natural resource, the sustainable management of groundwater also requires a multi-perspective approach that accounts for different drivers of change, and leverages different instruments to address the change. This paper complements the existing literature on this topic by exploring the use of a city's Master Plan as an instrument to create an enabling environment for the sustainable management of groundwater resources.

02

City Master Plans

A city's Master Plan is a long-term strategic blueprint that charts out the broad contours of the development landscape the city will take. It lays out the vision for the city for a set time period, and advocates the strategies that the city will have to take in order to achieve the vision. Often synonymous with a City Development Plan, Master Plans in India are typically prepared over a 20-year horizon but there are cities with 15- or 25-year Master Plans as well. Traditionally, Master Plans of cities across the globe have been solely concerned with land-use planning, making the connection between built and open spaces, social settings, and their surrounding environments. However, in recent years Master Plans have begun to shed the tag of being a purely land-use based plan and emerge as a strategic enabler to influence the direction the city will take to make it more vibrant, livable and productive.

For example, one of the targets of the Plan Melbourne (2017-2050) is to reduce its greenhouse gas emissions to net zero by 2050 to combat climate change. Similarly, Los Angeles' General Plan (2035) has marked Significant *Ecological Areas* to conserve genetic and physical diversity within LA County by designating biological resource areas that are capable of sustaining themselves into the future. The Tokyo Master Plan (2041) seeks to establish centers that increase economic vitality. Even in India, the Andhra Pradesh Capital Region Perspective Plan (2050) talks about a shift towards renewable energy, green certifications for buildings, and zero waste philosophies, among the other conventional content. From these examples, it is quite clear that the far-reaching implications of land use are finally being recognized, making it necessary to expand the role of a traditional, narrowly focused tool to encompass biodiversity, energy use, climate change, human health, food security and water security.

The current urban planning regime in India finds its roots in the Town and Country Planning Act of the United Kingdom of 1947. After the country received its independence from the UK, it undertook several policy initiatives to foster planned development of towns and cities in the country. Among the first of these was introducing the Delhi Development Act 1957 that led to the establishment of the Delhi Development Authority, which in turn paved the way for establishing almost 300 development authorities for as many cities. The 1980s saw the launch of India's first urbanization policy (1988), which acknowledged the role of cities in driving the country's economy and emphasized the necessity of integrating spatial and economic development of its urban centers. A major gamechanger was the enactment of the 74th Constitutional Amendment in 1992 that accentuated the need for local governance, and led to the setting up of urban local bodies or city governments and empowered them to undertake a range of responsibilities that include economic and spatial planned development of towns and cities.

Master Plans are also progressively becoming avenues for environment and natural resources protection.
In the Indian context, the Master Plan for Delhi (2021) sets out clear strategies for the conservation of natural environment assets, including forests, water bodies, natural drains.
So does the Mumbai Metropolitan Regional Plan (2036).
Similarly, the Master Plan for the city of Bengaluru (2031) has a special theme on protection and conservation of lakes and streams. Almost every city's Master Plan has incorporated elements of resource protection in some form or the other. Some Master Plans (e.g. Master Plan for Delhi, 2021; Chennai Master Plan 2026) even have dedicated sections for augmentation and protection of groundwater resources.
The Master Plan has several advantages for sustainable groundwater management in India:

- Master Plans are legally binding documents. Hence, any intervention proposed in the Master Plan has a legal connotation. If the interventions required for groundwater management under the Master Plan are not carried out by an appropriate agency, there can be legal consequences.
- A Master Plan is prepared by a development agency, which is usually directly under the State government. As pointed out earlier, water management is also a State subject in India. Thus, the actions for groundwater management in the city proposed under its Master Plan has a natural synergy with the State's vision for water as well as an increased chance of securing finances required for implementation.
- Water management in urban areas is typically done in silos, with different agencies managing different aspects of water. Sustainable groundwater management requires close coordination among these agencies. For example, groundwater recharge projects may require floodwater harvesting as well the use of treated wastewater, which are managed by different agencies. The Master Plan has the authority to get these agencies to coordinate their activities towards a common goal.
- Master Plans are expected to be made with citizen engagement and support. The citizens, therefore, have a voice in the making of the Plan. There is, therefore, a unique opportunity to make sustainable groundwater management a people's mandate.
- Master Plans are typically long-term plans. Incorporating elements of groundwater management in these Plans will, therefore, garner sustained attention and focus on this issue.

03 Methodology

A Master Plan has several tools and instruments that are used to shape and control the development trajectory of a city in line with the overall objectives of the Plan. Some of these can be used for the effective and sustainable management of groundwater in cities as well. This study follows a simple methodology of first highlighting these instruments, explaining their relevance in context of a Master Plan. These instruments include Floor Area Ratio; Land Use Planning; Transferable Development Rights; Urban Design Elements; Norms and Regulations; Sectoral Strategy; Interlinking Blues and Greens; Special Projects; and Economic Instruments. Each of these tools are widely used in planning, and many times in areas not necessarily for groundwater management. The fact that the purpose of the study is to demonstrate the application of these tools for sustainable groundwater management may make it interesting for planners and decision makers tasked with groundwater management.

Figure 4-2 *Cities whose Master Plans have been used as case studies in the study (Source: Authors' graphics/analysis)*

The study uses practical examples from the Master Plans of fifteen Indian cities—Andhra Capital Region, Bengaluru, Bhopal, Bhubaneshwar, Chandigarh, Chennai, Delhi, Gurgaon, Hyderabad, Jaipur, Kozhikode, Mumbai, Noida, Puducherry, and Surat to articulate the applications of the tools for groundwater management. These case studies have been taken from across the country as seen in the map in Figure 4-2.

“The use of FAR for groundwater management is particularly useful for new cities, or new areas within the city that are taken up for urbanization or redevelopment”

04

Master Plan Instruments for Groundwater Management

4.1. Floor Area Ratio (FAR)

The floor area ratio (FAR) is a density control tool for planning. It establishes the relationship between the total amount of usable floor area that a building has, or has been permitted to have, and the total area of the plot of land on which the building stands. Figure 4-3 presents a schematic of the FAR.

The ratio is determined by dividing the total or gross floor area of the building by the gross area of the plot. It can, therefore, be followed that a higher FAR ratio indicates high urban density. The local administration or planning authorities use FAR for zoning and density control.

The use of FAR for groundwater management is particularly useful for new cities, or new areas within the city that are taken up for urbanization or redevelopment. This aspect is important in the Indian context because the rate of urbanization in Indian cities has been on the rise for the last several years. Currently, about 34% of India’s population lives in urban areas (UN DESA, 2018). By 2030, this number is expected to go up to 40% (McKinsey Global Institute, 2010). Hence, going forward, extension of the urban areas in cities is inevitable. The growth of a city should ideally be linked to its carrying capacity that accounts for the natural resources

$$FAR = \frac{BUA}{PLOT\ AREA}$$

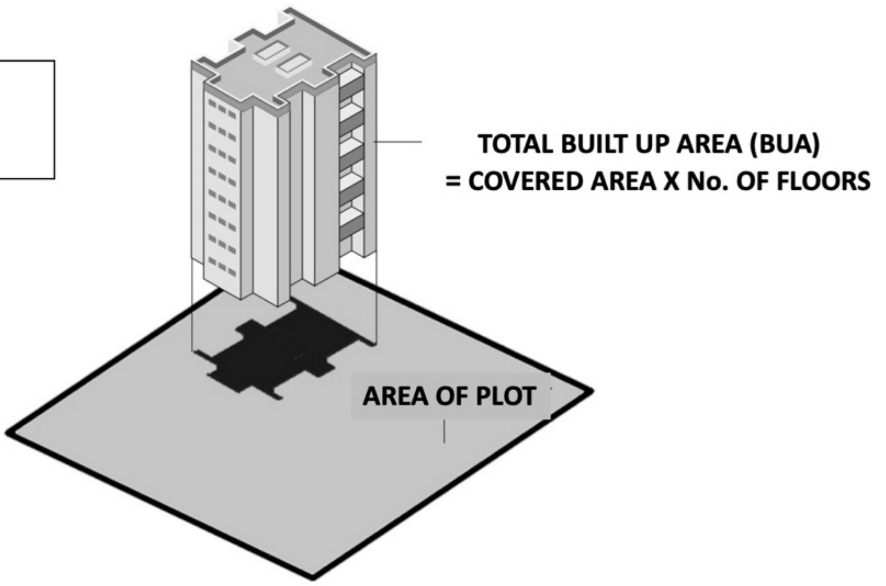


Figure 4-3 Representation of the Floor Area Ratio (FAR) (Source: Authors’ graphics/analysis)

required to support the growth. Groundwater is a key natural resource, and given that cities depend significantly upon groundwater for water supply, this becomes a vital factor in deciding the carrying capacity of the city. FAR can, therefore, be used to control the growth of city in accordance to the sustainable groundwater yield.

This instrument has been applied in Delhi, India's capital, to reduce stress on existing water resources. In 2013, Delhi initiated an exercise to urbanize some of the peripheral areas in the western region that are under agricultural land use. This was deemed necessary to meet the growing demand for housing infrastructure and other provisions.
The initial development of this extended area was planned with a FAR of 400 (high level of urbanization). However, it soon became evident that such a high FAR would put tremendous pressure on the water resources (including groundwater), which are already in a precarious state. As seen in Figure 4-4, the groundwater reserves across Delhi are mostly in a critical or semi-critical condition. The major concern for the authorities was that the originally envisaged FAR would not only create challenges for water availability, it could also lead to further exploitation of the underlying aquifers to the point of irreparable damage. This led them to reduce the proposed FAR by half, and in 2018, the policy for the development of this area was finalized with a FAR of 200. Water was, therefore, the single factor, for determining the extent of growth in Delhi.

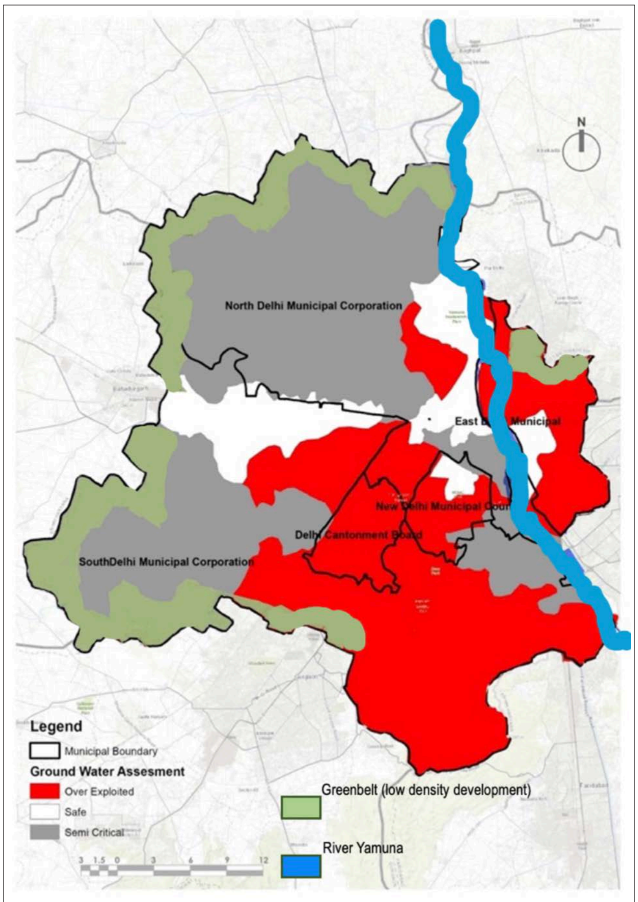


Figure 4-4 *Status quo of the groundwater resources in Delhi (Source: Authors' graphics/analysis; data from Central Ground Water Board, India)*

4.2. Land Use Planning

In its simplest form, land use planning is essentially assigning different areas of the city for specific uses. Typically, the major categories of these uses are residential, commercial, industrial, recreational, public and semi-public use, institutional, etc. These are usually marked in different colors on any Master Plan map. Figure 5 shows an example of a land use plan.

Land use planning is required to control the growth of the different activities in order to have an optimal balance among the activities and avoid excess of any particular activity. More importantly, in context of this paper, it helps in keeping a check on conflicting activities such as industrial and recreational (which comprises open spaces, green areas, water bodies) as the pollution from industries may have an adverse effect on the environmental assets and resources (e.g. groundwater).

From an urban groundwater management point of view, land use planning is particularly important for protecting areas that have implications for groundwater recharge. For example, such areas can be earmarked as parks or open areas in the land use plan to protect them from construction built up and allow for the natural infiltration of groundwater. Land use planning can also be used to assign a specific use typology to groundwater sensitive areas. These could include water bodies (lakes, ponds, wells) and wetlands. Each land use type is always associated with permissible and non-permissible activities. Hence, when water bodies and wetlands are assigned a specific land use, it becomes easier to prohibit activities that are known to exploit and/or pollute groundwater resources. Only activities that are not likely to affect the underlying groundwater may be permitted for this land use typology.

Most of the Indian cities have a land use designation for water bodies. Figure 4-6 shows a land use map for Hyderabad city, where land use category-8 is dedicated for water bodies (Light blue color). Water bodies are quite significant from a groundwater conservation and protection perspective because they are natural groundwater recharge zones in the city. Hence, it is imperative to protect these bodies, especially in Hyderabad where several of these have been lost to encroachment over the last decade. The protection of water bodies becomes even more significant in light of pollution from untreated domestic and industrial wastewater as well as septage from septic tanks. Assigning a specific land use and associated permissible activities for water bodies, therefore, can go a long way in groundwater conservation and protection.

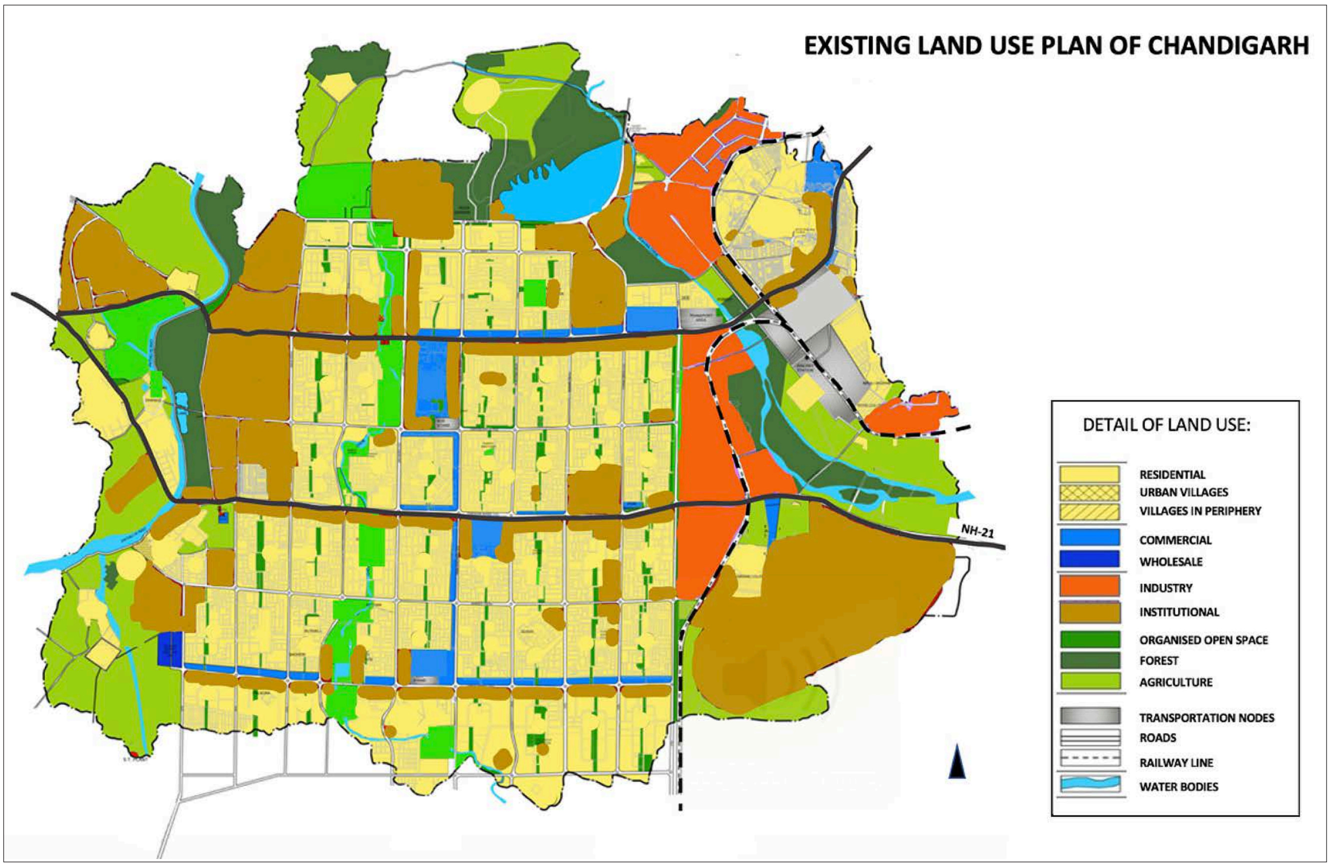


Figure 4-5 *Land use map for Chandigarh city (Source: Authors' graphics/analysis; data: Chandigarh Master Plan 2031)*

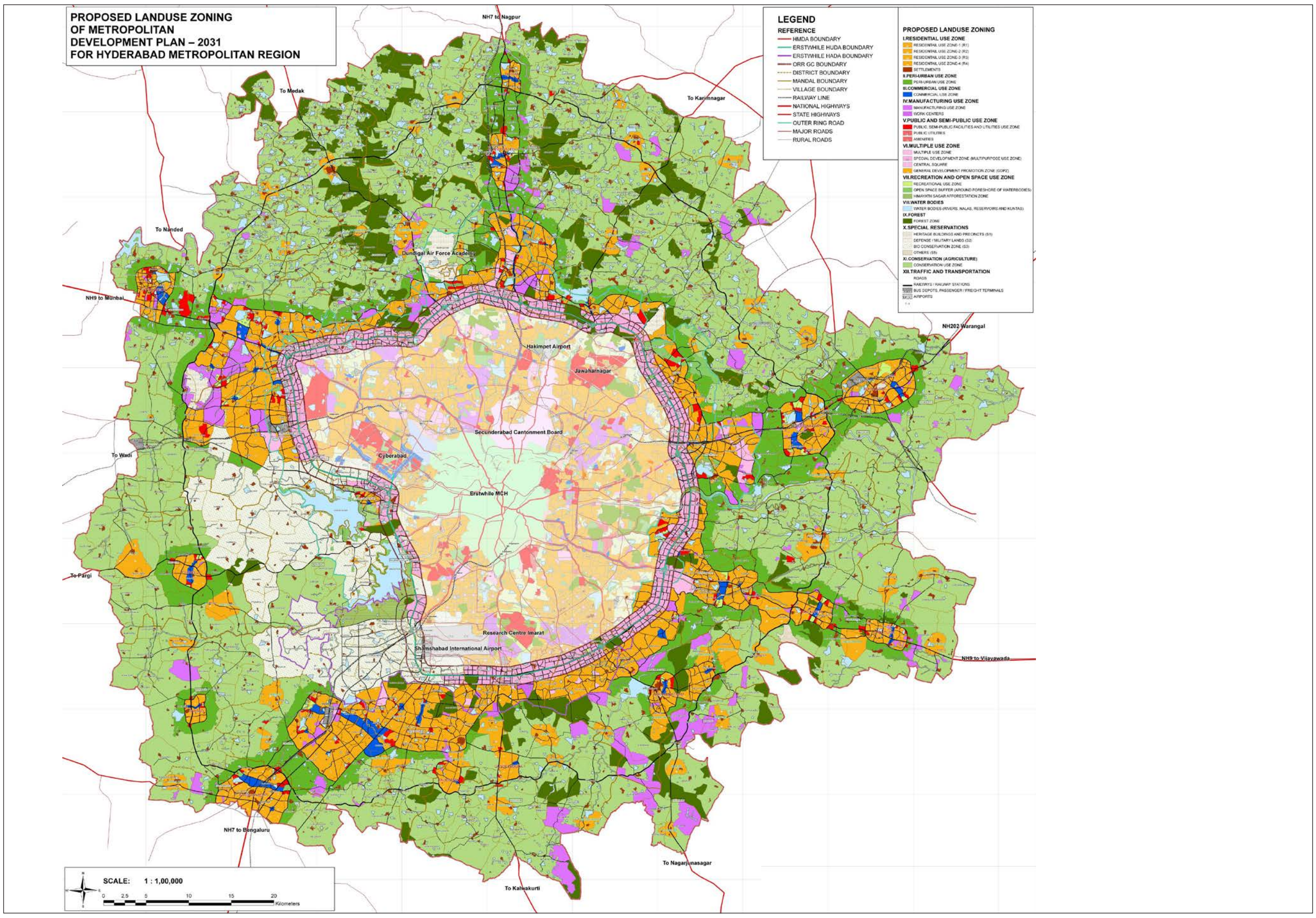


Figure 4-6 *Land use map for Hyderabad City (Source: Authors' graphics/analysis; data: Metropolitan Development Plan for Hyderabad 2031)*

In case of Hyderabad, there are several restrictions on activities in the land use category assigned for water bodies in the city's Master Plan. These include:

- No construction is permitted in the water body zone
- No building/ development activity is allowed in the bed of water bodies like river, or drain, and in the Full Tank Level (FTL) of any lake or pond.
- Water bodies must be maintained as a recreational/green buffer zone, and no building activity other than recreational use shall be carried out within
  - 30 meters from the boundary of lakes of area 10 Ha and above;
  - 9 meters from the boundary of lakes of area less than 10 Ha
  - 9 meters from the boundaries of a Canal
  - 2 meters from the defined boundary of drains.

Another example of using land use planning for groundwater management can be found in the City Development Plan for Gurgaon (2031). Gurgaon city borders the national capital Delhi in the South. The Development Plan of the city has marked Eco-sensitive zones primarily with the intent to protect the Aravalli mountain range. Groundwater extraction is prohibited not only in these zones but up to an extent of 1 km from the periphery.

"TDRs can serve as a useful tool to protect potential groundwater recharge zones that are under privately owned land"

4.3. Transferable Development Rights

As the name suggests, Transferable Development Rights (TDR) is an incentive given to landowners to sell development rights of their land in a particular area (sending area) and use these rights to increase the density of development at another designated location (receiving area). The concept is explained through a schematic in Figure 4-7. Through this mechanism, the landowners are allowed to build over and above the permissible FAR in specific locations of the receiving area. Traditionally this mechanism has been used to compensate land owners when the Government undertakes compulsory acquisition of individual land parcels for creating infrastructure projects. TDRs are obtained in the form of certificates, which the landowners can use themselves or sell to other interested parties.

TDRs can serve as a useful tool to protect potential groundwater recharge zones that are under privately owned land. The city of Hyderabad has adopted TDRs to conserve its natural heritage zones. Several of these heritage zones have traditional water bodies that area are excellent avenues for groundwater recharge. Landowners of areas that fall under natural heritage zones are provided a TDR incentive up to 400 per cent of the land they surrender. For example, if the landowners surrender a property of 100 m^2 in the heritage zone, they would be allowed to construct a four-story property on a plot of 100 m^2 in the receiving area. They also have the flexibility to sell the rights to a developer who already owns land in the receiving area. In such cases, the developer can avail of the extra incentives on the plot of land they own.

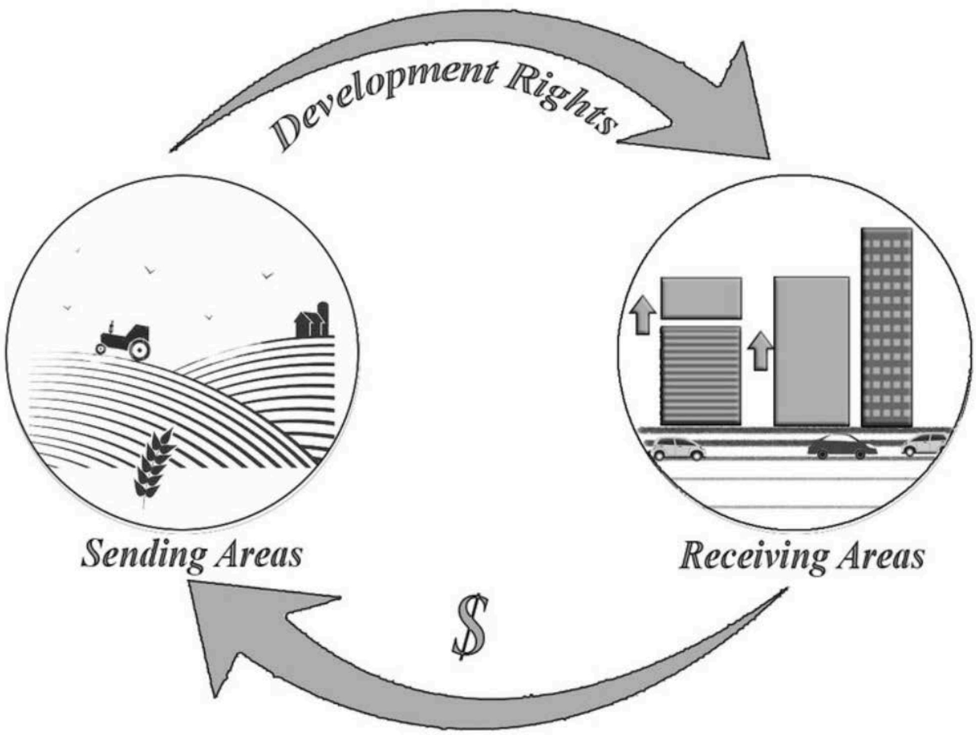


Figure 4-7 Concept of Transferable Development Rights (Source: Authors' graphics/analysis)

4.4. Urban Design Elements

Urban design is creating spaces that enhance the relationship between people and the built and natural environment. The built environment includes buildings, streets, public spaces, transport, etc., and the natural environment includes features such as water bodies, rivers, forests, shorelines, etc. In context of groundwater management (and water in general), an urban design philosophy called Water Sensitive Urban Design (WSUD) is becoming increasingly popular in cities across the globe. In some parts of the world, WSUD may be equivalent to Low Impact Development in North America and Sustainable Urban Drainage Systems in Europe. Introduced in Australia in the early 1990s, WSUD is the process of integrating water cycle management with the built environment through planning and urban design. It has two fundamental principles. First, all elements of the water cycle and their interconnections are considered concurrently to achieve an outcome that sustains a healthy natural environment while meeting human needs. Second, the consideration of the water cycle is made from the outset, and throughout the design and planning process. Accordingly, water management solutions seek to meet the expectations and aspirations for design of successful places (CIRIA, 2013). Figure 4-8 contextualizes the WSUD concepts in a typical urban setting.

WSUD elements that are particularly helpful for groundwater management are raingardens; swales; constructed wetlands; porous pavement; rainwater and storm water harvesting; green infrastructure (green roofs, green facades and tree pits); and infiltration trenches. The WSUD philosophy is clearly evident in the Andhra Pradesh Capital Region Perspective Plan (2050). Among the other contemporary planning philosophies, the Plan has adopted WSUD for urban storm water runoff management (which has direct implications for groundwater augmentation) with the following objectives:

- Protecting and improving the water quality of water draining from urban environments into creeks, rivers and wetland
- Restoring the urban water balance by maximizing the reuse of storm water, recycled water and grey water
- Conserving water resources through reuse and system efficiency;
- Integrating storm water treatment into the landscape so that it offers multiple benefits such as improved water quality, wildlife habitat, recreation and open public space; and reducing peak flows and runoff from the urban environment simultaneously providing for infiltration and groundwater recharge.

The Draft Bhopal Development Plan (BDP) 2031 is another unique element where a land suitability analysis has been carried out using parameters such as topography, gradient, soil condition, existing land use, geomorphology, etc. to identify and integrate WSUD elements such as drains and wetlands into the development landscape.

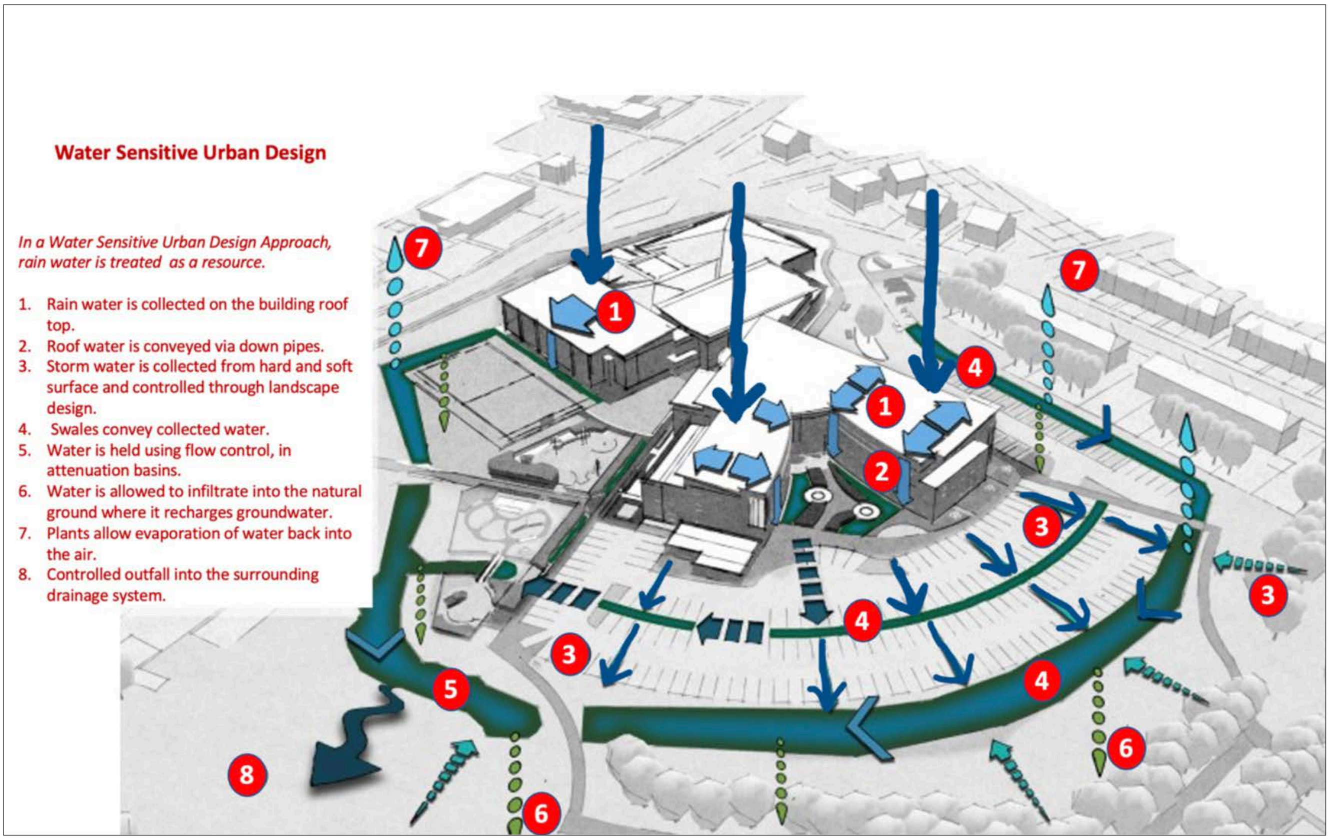


Figure 4-8 Conceptualizing water sensitive urban design (Source: Authors' graphics/analysis)

4.5. Regulations and Norms

An integral function of Master Plans is to prescribe regulations and norms for different aspects to prevent activities that are detrimental to the overall growth of the city on multiple fronts. Regulations are a set of rules that are enforced to ensure that the development of the city proceeds as per the Master Plan. It is, therefore, an instrument to help translate the Master Plan on the ground. Norms represent the desirable levels of services that need to be achieved through the various planning interventions.

There are a number of norms and regulations that can be adopted through Master Plans to protect and conserve groundwater resources. A pertinent example of this can be found in the Mumbai Metropolitan Regional Plan (2036). The plan stipulates that "*construction of basements may be allowed subject to the condition that no objection certificate is obtained from the State Ground Water Authority to the effect that such construction will not adversely affect free flow of groundwater in that area*". Similarly, the Gujarat General Development Control Regulations, (2017) requires that "*Maximum of 50% of the total open space including marginal open spaces and common plot of a building-unit shall be paved. The remaining shall be permeable for rain water percolation*"

Another example can be found in the Development Plan for Surat (2035). Surat is among the largest cities in Western India. The city has witnessed very rapid growth over the last two decades, which has put enormous stress on the city's groundwater resources. There is good potential for use of surface water resources to meet the water demand of the city. However, due to a lack of piped supply network in all developing urban areas, for all practical purposes, groundwater is the only source of water for the city. To protect this fast diminishing resource, the Development Plan has made it mandatory for private plots larger than 4000 sq. m. and high-rise buildings to install rainwater harvesting units for recharging the groundwater.

A variant in the norms and regulations can be found in the Chandigarh Master Plan (2035). Chandigarh is a city in North India, which relies more on surface water that groundwater for its supply. However, it also taps into its deep confined aquifers as part of the supply mix. Responding to growing concerns regarding recharge of these aquifers, and their further exploitation, the Master Plan has mandated all new buildings to install water efficient fixtures with a view to reduce the demand for fresh water. It is expected that at least a 25% reduction in water consumption can be achieved through such an arrangement. Here protection of groundwater resources is being targeted through demand management.

4.6. Formulating a Sectoral Strategy

A Master Plan provides an overall strategic direction to a city's development landscape for the planning horizon. In many plans, detailed strategies for specific development sectors, such as housing, transport, physical and social infrastructure, heritage, and environment, are also elaborated. The Master Plan, therefore, offers a unique opportunity for a dedicated groundwater management strategy to be rolled out.
The level of detail of the strategy will depend upon the need, information available and urgency of action. An example of a succinct strategy can be found in the Master Development Plan for Jaipur (2021). The city of Jaipur is located in Western India in the desert state of Rajasthan. Historically, it has depended heavily on groundwater. However, in recent years, it has been receiving a majority of water from two surface water reservoirs—Bisalpur and Isarda both built on the Banas River. The yield from these reservoirs has been in decline lately, leading to serious questions about the reliability of the supply from these reservoirs. The City Development Plan has made it abundantly clear that the dwindling supply from the reservoirs cannot be used as a premise to exploit the already stressed groundwater resources. To address the problem, the Development Plan has proposed a pan city strategy for the large-scale use of water recycling and water harvesting across the city. It outlines the broad contours of the strategy with instructions to the local government detail out a comprehensive action plan for this purpose.

Likewise, the Master Plan for Kozhikode Urban Area (2035) in South India provides a detailed strategy for groundwater management. Groundwater is currently the major source of water supply in the city, and its continuous abstraction over time has led to several areas falling under 'over-exploited' and 'semi critical' categories. The Plan recognizes the urgent need for recharging groundwater aquifers and proposes a comprehensive groundwater resource management strategy based on a scientific study carried out by the Central Ground Water Board. The strategy has:

- Identified artificial recharge structures that would work best in the city. These include percolation tanks (suitable for most areas in the city), check dams (across small streams), sub-surface dykes (a barrier constructed across the river below the riverbed to arrest subsurface flow to increase the recharge in upstream portions of the aquifer), dug wells, and roof top rainwater harvesting.
- Directed local authorities to carry out periodic desiltation of tanks/ ponds to augment the groundwater recharge.
- Provided directions on the conjunctive use of groundwater, rainwater and surface water.
- Emphasized watershed development for better water management.
- Mainstreamed community awareness programmes and training programmes into the annual plans of the concerned local agencies.

4.7. Interlinking Blue and Green Infrastructure

Linking the blues (water bodies) and greens (forests, parks, trees) is a widely propagated concept in Master Plans.
This is usually done to maintain a continuum of the blue green assets by creating a seamless network of parks and greens by integrating the ponds, natural features, canal network and water bodies. There are several benefits of doing this.
First, it helps urban biodiversity, especially the fauna, to thrive by providing it with a long continuous stretch of area that is free from development. Second, it adds to the aesthetics of the city and provides its residents with an eco-friendly recreational avenue. Third, in context of this paper, because the stretch of network will mostly have permeable surfaces, it facilitates groundwater recharge, thereby supporting the overarching objectives of groundwater protection and augmentation. Figure 4-9 presents an example of a blue green network.

An example of the interlinking of blue green infrastructure can be found in the Master Plan for Noida (2031). Noida is a city in North India, in very close proximity to the national capital Delhi. The city is one of the greenest in the country and has an abundance of water bodies in different parts of the city.
The city has long continuous stretches of forest land, called green belt, in some regions. The Plan has called for linking parks and green areas with this green belt, landscaped with water bodies to act as groundwater recharge system.

4.8. Proposing Special Projects

A unique attribute of a Master Plan is that it has the authority to create the grounds for special projects that are deemed necessary for the city. These projects could range from transport to housing to infrastructure to recreational assets, with the condition that these are absolutely imperative for the city. Discussed below are three examples of Master Plans that have proposed projects for groundwater protection and management.

The first example is in the city of Surat in western India.
The city has an industrial estate called Pandesara that is spread over an area of about 2.8 km^2. There are about 400 industrial units operating in this estate, out of which 119 units are water-based industries comprising largely textile processing units and chemical industries. The current water demand at Pandesara is estimated at approximately 100 Million Liters per Day (MLD), of which nearly 55 MLD is met through municipal potable water supply that is almost entirely dependent on groundwater. The remaining demand is met directly through private sources including borewells and water tankers.
The Pandesara Industrial Estate is just 5 km away from the Sewage Treatment Plant at Bamroli (100 MLD capacity), in which secondary treatment of wastewater takes place. Realizing that this wastewater is a good source of water, the Surat Master Plan (2035) proposed setting up a 40 MLD capacity tertiary treatment unit to treat the secondary treated water from Bamroli Sewage Treatment Plant to supply industrial grade water to Pandesara Industrial Estate.

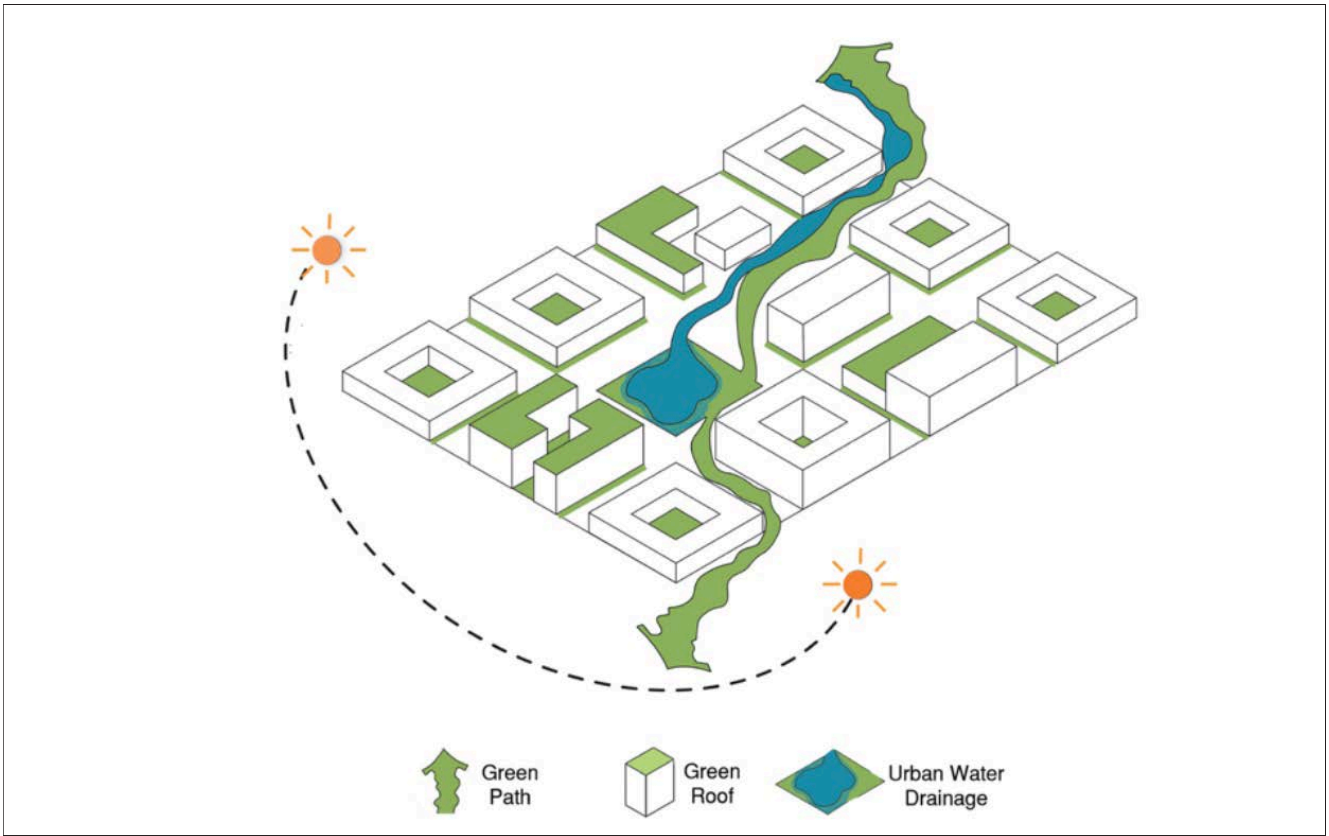


Figure 4-9 Schematic of a Blue Green Network (Source: Authors' graphics/analysis)

This would reduce the demand for freshwater and thereby alleviate the pressure on groundwater resources of the city.

The second example is from the city of Panaji in the State of Goa. Panaji city is surrounded by water bodies and has a high groundwater table, where water is available at a depth of around 1 to 1.5 m below the surface. The sewerage network in Panaji only covers the core city area, and does not service the urban fringe areas. Furthermore, the city has an informal slum area that does not have sewerage coverage. Both these areas discharge untreated wastewater into the various water bodies of the city, which have become a major source of groundwater pollution and pollution of the River Mandovi. To address this issue, the City Development Plan for Panaji (2041) has proposed a project (Sewerage and Sanitation-Underground Drainage) to be rolled out on a priority basis. The salient features of the project are:

- Identification and replacement of the old sewage collection pipes from the city area of Panaji and provision of new pipelines.
- Upgrading the pumping stations based on vacuum pumping technology
- Improvement of existing public toilets within the city
- Provision of a new sewage collection network in the non-covered areas.

The third example is from the city of Puducherry. The only existing source of water supply to the urban area is groundwater. The total amount of water extracted for water supply is 112 MLD, because of which the groundwater table has been continuously decreasing. As a result, water quality is also hampered. However, in the absence of any alternative source, the city has had to continue to depend upon groundwater. To address this challenge, the Comprehensive Development Plan for Puducherry Planning Area (2035) has proposed a desalination plant of 41.37 MLD to partially meet the demand. The Plan has also allocated 15 hectares of land for the desalination plant.

4.9. Economic Instruments

Economic instruments are a very effective tool to support any policy or strategy that requires different sections of society and stakeholders to contribute to the successful implementation of the policy/strategy. The most commonly used economic instruments are taxes, subsidies, incentives, rebates, and penalties, which have been used in several contexts, including groundwater management.

A unique example of the use of an economic instrument for groundwater management is seen in the Master Plan for Noida (2031). This is in the form of groundwater storage credits. The city of Noida receives water from both surface water sources (River Ganga) as well as groundwater. In recent years, water from the surface sources has become unreliable for a good part of the year. For this reason, the city has had to increase its groundwater exploitation rate, which is a point of concern. To ensure that there is adequate recharge to offset the exploitation rate, the Master Plan requires industries to apply for Zero-Discharge licences making it mandatory for them to install inhouse waste water recycling plants, and use the treated effluent for its operations. Any surplus treated effluent may be used to recharge groundwater resources for which the industries earn storage credits. Hence, the storage credit is equal to the amount of treated wastewater used for groundwater recharge. The industries can then use up these credits to withdraw water for use from permitted recovery wells.

05

Groundwater Management in Green Field and Brownfield Development

In the urban context, there are two broad categories of planning—greenfield and brownfield. Greenfield refers to brand new development, where there are ample opportunities for all the planning instruments for groundwater management mentioned in this paper to be applied directly. In such areas, development density control would be a crucial target to ensure sustainable resource utilization and conservation, which can be done through FAR allocation. However, the direction and pattern of development also plays an important role to reduce resource use and recover natural resources. In greenfield developments, this can be done through revision of local planning and zoning ordinances to encourage the use of low impact development. For instance, it may be necessary to first update the local comprehensive plan to set a goal for open space and conservation planning and design.

Brownfield areas are already developed, and are typical to most Indian cities. Given that a large part of the planning area is already developed, there may be constraints in applying some of the planning instruments in such areas. For example, FAR control will have limitations because it is impossible to reduce the FAR in areas that have already proceeded with development at a higher FAR. Furthermore, because of the presence of unauthorized colonies and informal settlements in brownfield areas, there is comparatively less scope to some of the solutions that are very much possible with greenfield development. Table 4-1 presents a comparative analysis of the efficacy of planning instruments in greenfield and brownfield areas.

It must be noted that, while there are constraints in brownfield areas, there is still great potential for implementing the planning instruments for groundwater management if the planners have a good contextual understanding of the areas within the city. For example, in old settlements (which are traditionally difficult to plan for) the planning will need to focus on micro scale interventions. Most of the old settlements have water conservation structures like wells, ponds, step wells (ancient wells where steps were constructed for people to go down the well and withdraw water), etc. Invariably, such structures are an excellent avenue for groundwater recharge. The Master Plan can earmark these areas as eco sensitive zones to prevent developmental activities in these areas. Aspects of this have been attempted in the Redevelopment Plan for the old city of Jaipur. Similarly, all the other planning instruments mentioned in this paper can be applied in brownfield areas with some customization based on site-specific understanding.

Table 4-1 Efficacy of planning instruments for groundwater management in greenfield and brownfield development (Source: Authors' analysis)

	Master Plan Master Plan	Brownfield development	Greenfield development
1	Floor Area Ratio (FAR)	o This tool has limited application in brownfield because it is difficult to reduce the FAR in areas originally awarded a high FAR. o FAR can serve as a powerful tool when pockets of brownfield development are taken up for redevelopment.	o FAR can be used to control the density and growth of the city to match the sustainable yield of resources (including groundwater) o FAR can be used as a lucrative incentive to encourage property owners to adopt groundwater conservation practices. E.g. if property owners make provision for large scale groundwater recharge on their properties, they can be permitted a higher FAR than originally allowed.
2	Land-use planning	Change in land use (CLU) is very common practice in brownfield development. Wherever possible, CLUs can be used judiciously to earmark groundwater sensitive areas as 'no development zones' or areas under special protection.	There is much more flexibility for land use planning for groundwater management in greenfield. For example, low lying areas that have good groundwater recharge potential can be assigned a 'recreational' land use. Parks and recreational greens, which are compatible with this use, may be then taken up in these areas.
3	Transferable Development Rights (TDR)	In brownfield, TDRs will typically work where there is scope within the city to serve as a receiving area, where the transferred development rights can be used. TDR can then be used in conjunction with CLU to good effect.	Ideally, TDR will not be required in greenfield because there is no land ownership issue to begin with. Hence, planners have all the flexibility to reserve groundwater sensitive zones under some kind of protection.

4	Urban Design Elements	The most feasible urban design elements in brownfields are those that do not require much land, or elements that can be integrated within the already green/open areas. Interventions such as bioswales, raingardens, green roofs, vertical forests, etc. are almost always possible. Depending upon the built fabric of the city, other interventions such as detention ponds, infiltration trenches, etc. may also be considered and taken up.	Any urban design element can be taken up in greenfield, even those that require significant land area such as constructed wetlands, artificial water bodies, etc.
5	Regulations and Norms	While it is very much possible to introduce new regulations and norms in brownfield, it becomes challenging to enforce when the areas that require interventions are already built up. For example, new regulations related to maintaining a buffer for natural drains (which are excellent avenues for groundwater recharge) become difficult to enforce if these buffers are already encroached upon.	Introducing regulations and norms in greenfield is quite easy. However, it is equally important to set up robust monitoring mechanisms to ensure that these regulations are complied with.
6	Formulating a sectoral strategy	This is equally possible and feasible in both brownfield and greenfield. In brownfield, the directions of the strategy will have to account for existing development and ground conditions, while in greenfield the directions can help inform the planned development landscape.	
7	Interlinking blue and green infrastructure	o Existing development may pose challenges for holistic interlinking of blue green infrastructure but such linkages may be taken up in parts, wherever feasible. In areas where this is not feasible currently, it can be taken up when these areas are taken up for redevelopment. o Private property owners will need to be incentivized (e.g. through reduction in property taxes) to contribute to the interlinking.	o Interlinking the blue and green network can be taken up at the planning stage itself in greenfield. The network can be marked as a no-development zone in the land use plan with only eco-friendly recreational activities allowed. o It will be very important to protect this network from unwanted encroachment through boundary protection measures.
8	Proposing special projects	This is equally possible and feasible in both brownfield and greenfield. In brownfield, a limiting factor for the special projects may be land requirements. In contrast, the level of ambition can be scaled up in greenfield developments.	
9	Economic instruments	This is equally possible and feasible in both brownfield and greenfield. In fact, there is hardly any difference in the strategy adopted to roll out the instruments in both cases.	

06
Conclusions

Sustainable groundwater protection and management is a complex endeavor that requires interventions in diverse areas such as policy and law, engineering and technology, economics, social equity and behavioral change, among others. This paper focuses on planning-related interventions. Most of these interventions are 'proactive' as opposed to 'reactive', meant to avert a groundwater crisis from happening in the first place. As Indian cities progress in their paths towards economic development, it will be important to ensure that groundwater resources are managed in a sustainable way. Given the land crunch in Indian cities, going forward, the opportunities for greenfield development are going to be fairly limited. Planning authorities will, therefore, need to increase their focus on brownfield areas, exploring the customized use of planning instruments, to protect, conserve, and manage the overall groundwater resources of the city.

"It will be important to ensure that groundwater resources are managed in a sustainable way"

While the paper has been developed in an Indian context, it has implications for other groundwater stressed cities in the world as well, given that urban planning is a global paradigm practiced, albeit in different styles, across the world.

References

Abrishamchi, A., Fard, F. K. & Taghavi, A. (2020). Planning for groundwater sustainable use: A case study in Nishapur Plain, Iran. *Agricultural Water Management* Volume 229, Article 105835.

Abu-Bakr, H. A. (2020). Groundwater vulnerability assessment in different types of aquifers. *Agricultural Water Management* Volume 240, Article 106275.

Adhikari, R. K., Mohanasundaram, S. & Shrestha, S. (2020). Impacts of land-use changes on the groundwater recharge in the Ho Chi Minh city, Vietnam. *Environmental Research*, Volume 185, Article 109440.

Ahmad, A. Y., Al-Ghouti, M.A. (2020). Approaches to achieve sustainable use and management of groundwater resources in Qatar: A review. *Groundwater for Sustainable Development* Volume 11, Article 100367.

Ashwell, N.E.Q., Peterson, J.M. & Hendricks, N.P. (2020). Optimal groundwater management under climate change and technical progress. *Resource and Energy Economics*, 51, pp. 67-83.

Carmon, N., Shamir, U. & Meiron-Pistiner, S. (1997). Water-sensitive urban planning: Protecting groundwater. *Journal of Environmental Planning and Management*, 40(4), pp. 413-434.

Central Ground Water Board (2016). Aquifer mapping and ground water management plan of NCT Delhi. Accessed 19 October 2020 from http://cgwb.gov.in/AQM/NAQUIM_REPORT/Delhi/old/Naquim%20Report%20Delhi%20.pdf.

CIRIA. (2013). Water Sensitive Urban Design in the UK – Ideas for built environment practitioners. Accessed 19 October 2020 from https://www.susdrain.org/files/resources/ciria_guidance/wsud_ideas_book.pdf.

Das, J., Rahman, A.T.M.S, Mandal, T., Saha, P. (2020). Challenges of sustainable groundwater management for large scale irrigation under changing climate in Lower Ganga River basin in India. *Groundwater for Sustainable Development*, Volume 11, Article 100449.

India WRIS. (2020). Water Resources Information System. https://indiawris.gov.in/wris/#/.

Jiménez-Madrid, A., Martínez-Navarrete, C. & Jiménez-Fernández, P. (2017). The integration of groundwater protection into land-use planning, certification and standardization of quality of urban supply systems. *Procedia Engineering*, 209, pp. 148-155.

Khan, A., Govil, H., Taloor, A.K. & Kumar, G. (2020). Identification of artificial groundwater recharge sites in parts of Yamuna River basin India based on Remote Sensing and Geographical Information System. *Groundwater for Sustainable Development*, Volume 11, Article 100415.

Lavoie, R., Lebel, A., Joerin, F. & Rodriguez, M.J. (2013). Integration of groundwater information into decision making for regional planning: A portrait for North America. *Journal of Environmental Management*, 114, pp. 496-504.

Lalehzari, R. & Kerachian, R. (2020). Developing a framework for daily common pool groundwater allocation to demands in agricultural regions. *Agricultural Water Management*, Volume 241, Article 106278.

Mautner M.R.L., Foglia, L, Herrera, G.S., Galán, R. & Herman J.D. (2020). Urban growth and groundwater sustainability: Evaluating spatially distributed recharge alternatives in the Mexico City Metropolitan Area. *Journal of Hydrology*, Volume 586, Article 124909.

McKinsey Global Institute. (2010). India's urban awakening: Building inclusive cities, sustaining economic growth.

Niti Aayog (2018). Composite Water Management Index: A tool for water management. Accessed on 19 October 2020 from https://niti.gov.in/writereaddata/files/document_publication/2018-05-18-Water-Index-Report_vS8-compressed.pdf.

Patel, P.M., Saha, D. & Shah, T. (2020). Sustainability of groundwater through community-driven distributed recharge: An analysis of arguments for water scarce regions of semi-arid India. *Journal of Hydrology: Regional Studies*, Volume 29, Article 100680.

Qian, H., Chen, J. & Howard, K.W.F. (2020). Assessing groundwater pollution and potential remediation processes in a multi-layer aquifer system. *Environmental Pollution*, Volume 263, Part A, Article 114669.

Ruiz, G. (2015). Estimation of the Groundwater Recharge in the Aquifer of the Mexico City. *Procedia Environmental Sciences*, 25, pp. 220-226.

Sayed, E., Riad, P., Elbeih, S.F., Hassan, A.A. & Hagras, M. (2020). Sustainable groundwater management in arid regions considering climate change impacts in Moghra region, Egypt. *Groundwater for Sustainable Development* Volume 11, Article 100385.

Thomann, J.A., Werner, A.D., Irvine, D.J. & Currell M.J. (2020). Adaptive management in groundwater planning and development: A review of theory and applications. *Journal of Hydrology*, Volume 586, Article 124871.

UN DESA. (2018). World Urbanization prospects. Accessed 19 October 2020 from https://population.un.org/wup/.

Wakode, H.B., Baier, K., Jha, R. & Azzam, R. (2018). Impact of urbanization on groundwater recharge and urban water balance for the city of Hyderabad, India. *International Soil and Water Conservation Research*, 6(1), pp. 51-62.

World Bank. (2012). India Groundwater: a Valuable but Diminishing Resource. Accessed on 19 October 2020 from https://www.worldbank.org/en/news/feature/2012/03/06/india-groundwater-critical-diminishing.

______. (2019). Helping India Manage its Complex Water Resources. Accessed on 19 October 2020 from https://www.worldbank.org/en/news/feature/2019/03/22/helping-india-manage-its-complex-water-resources.

Yar, P. (2020). Urban development and its impact on the depletion of groundwater aquifers in Mardan City, Pakistan. *Groundwater for Sustainable Development*, Volume 11, Article 100426.

Weblinks to the Master Plans of Indian cities referenced in this study

Andhra Pradesh Capital Region Perspective Plan (2050)
https://crda.ap.gov.in/apcrdav2/views/masterplansDraft.aspx.

Master Plan for Bengaluru (2031)
https://opencity.in/pages/bda-revised-master-plan-2031-all-documents.

Bhopal Development Plan (2031)
http://mptownplan.gov.in/LU-panel/Bhopal/Amrut/ENGLISH/VOL1.pdf.

Chandigarh Master Plan (2035)
http://chandigarh.gov.in/cmp_2031.htm.

Chennai Master Plan (2026)
http://www.cmdachennai.gov.in/smp_main.html.

City Development Plan Gurgaon (2031)
https://assetyogi.com/wp-content/uploads/2014/10/Notification-Gurgaon-Manesar-Master-Plan-2031.pdf.

City Development Plan for Panaji (2041)
http://ccpgoa.com/images/Revised%20City%20Development%20Plan%20for%20Panaji%202041.pdf.

Comprehensive Development Plan for Puducherry Planning Area (2035)
https://ppa.py.gov.in/comprehensive-development-plan.

Development Plan for Surat (2035)
https://www.sudaonline.org/wp-content/uploads/2017/03/SUDA-DP-2035-report-final-22.02.2017.pdf.

Master Plan for Delhi (2021)
http://52.172.182.107/BPAMSClient/seConfigFiles/Downloads/MPD2021.pdf.

Master Plan for Noida (2031)
https://noidaauthorityonline.in/en/article/master-plan-for-noida.

Master Development Plan for Jaipur (2021)
https://jda.urban.rajasthan.gov.in/content/raj/udh/jda---jaipur/en/town-planning/master-development--plan-2025.html#.

Master Plan for the Kozhikode Urban Area (2035)
https://kozhikodecorporation.lsgkerala.gov.in/system/files/2019-06/master-plan-kozhikode-corp-report.pdf.

Metropolitan Development Plan for Hyderabad (2031).
https://www.hmda.gov.in/masterplan/.

Mumbai Metropolitan Regional Plan (2036)
https://mmrda.maharashtra.gov.in/regional-plan.

5

Study on Zones Classification, Management and Control Methods Based on Groundwater Functions in China

Yuanyuan Li, Lili Yu, Yan Yang, Fengyue Sun,Yueyuan Ding, Jie Hou, Fei Chen and Shinan Tang

Yuanyuan Li, General Institute of Water Resources and Hydropower Planning and Design, Ministry of Water Resources (GIWP), Beijing, China. e-mail: liyuanyuan@giwp.org.cn
Lili Yu, GIWP, Beijing, China. e-mail: yulili@giwp.org.cn
Yan Yang, GIWP, Beijing, China. e-mail: yangyan@giwp.org.cn
Fengyue Sun, GIWP, Beijing, China. e-mail: sunfengyue@giwp.org.cn
Yueyuan Ding, GIWP, Beijing, China. e-mail: dingyueyuan@giwp.org.cn
Jie Hou, GIWP, Beijing, China. e-mail: houjie@giwp.org.cn
Fei Chen, GIWP, Beijing, China. e-mail: chenfei@giwp.org.cn
Shinan Tang, GIWP, Beijing, China. e-mail: tangshinan@giwp.org.cn

Highlights

- Industrial water recycling systems provide water intensive industries with greater control over water and wastewater costs and eliminate dependencies on external water supplies.
- Industrial water recycling can be achieved via external "end-of-pipe" and internal systems and use a variety of treatment processes to remove suspended solids, reduce colour and salts and recovery energy.
- The unit cost ($/m^3) of industrial water recycling can exceed the cost of water supply by a factor of 1.5 to 2, however, the recycling schemes can be justified using triple bottom line (TBL) and Life Cycle Assessment (LCA) techniques which account for project externalities.
- Unlike municipal waste recycling, which has national guidelines for water quality and compliance, industrial water recycling is regulated at a state level. In addition, barriers to water recycling exist in food processing for export markets, particularly red meat exports.

Abstract

China has a vast territory with its natural conditions of groundwater varying greatly from place to place. Various interactions occur ceaselessly between groundwater and the water cycle, ecological environment and geological environment. Diversification in people's needs for groundwater results in different standards and regulations for groundwater exploitation and protection. In order to scientifically and rationally manage groundwater according to the different characteristics in each region, this research tries to identify the dominant function of groundwater at the regional level, and classify the groundwater functional zones. Based on an analysis of the current state of groundwater exploitation and future development needs, an overall groundwater management framework, along with control indicators of groundwater exploitation and water table, have been formulated for each functional zone accordingly. This paper is the summary of concerns arising from the definition, classification method, status evaluation and management measures of groundwater function zoning, based on the work of national groundwater function zoning in China from 2005 to 2013.

Keywords

Groundwater function, groundwater functional zones, groundwater control methods, groundwater overexploitation, governance

01

Groundwater Resources in China

Groundwater is a key component of water resources, an important element for ecology and environment, and it is one of the essential water sources for China's economic and social development. Since the 1970s, the scale of groundwater exploitation and utilization in China, especially in North China, has been expanding. The large-scale exploitation and utilization of groundwater has resulted in serious groundwater problems. Some regions are facing aquifer drainage, damage or loss of strategic reserve function, land subsidence, ground fissure, sea (salt) water intrusion, land desertification and a series of serious environmental and geological problems. In combination with the increasingly serious groundwater pollution situation, those problems bring great concerns to the economic and social development, human health, and ecology and environment (Wang *et al*., 2007; Tang *et al*., 2012).

1.1. Quantity and Distribution of Groundwater Resources

According to Investigation and assessment of water resources development and utilization in China (2014), the average annual quantity of renewable groundwater resources in China from 1980 to 2000 was 821.8 billion m^3, and the average quantity of groundwater resources per km^2 in China was 96,000 m^3/km^2. Different climatic characteristics determine the natural conditions of groundwater resources, which have huge variations in different regions. The quantity per km^2 of renewable groundwater resources increases from west to east and from north to south. The South China region has 168,000 m^3/km^2 and the North China region has 48,000 m^3/km^2, while in many areas of Northwest China, the figure is even less than 30,000 m^3/km^2. The distribution of the quantity of renewable groundwater resources per km^2 in China is shown in Figure 5-1.

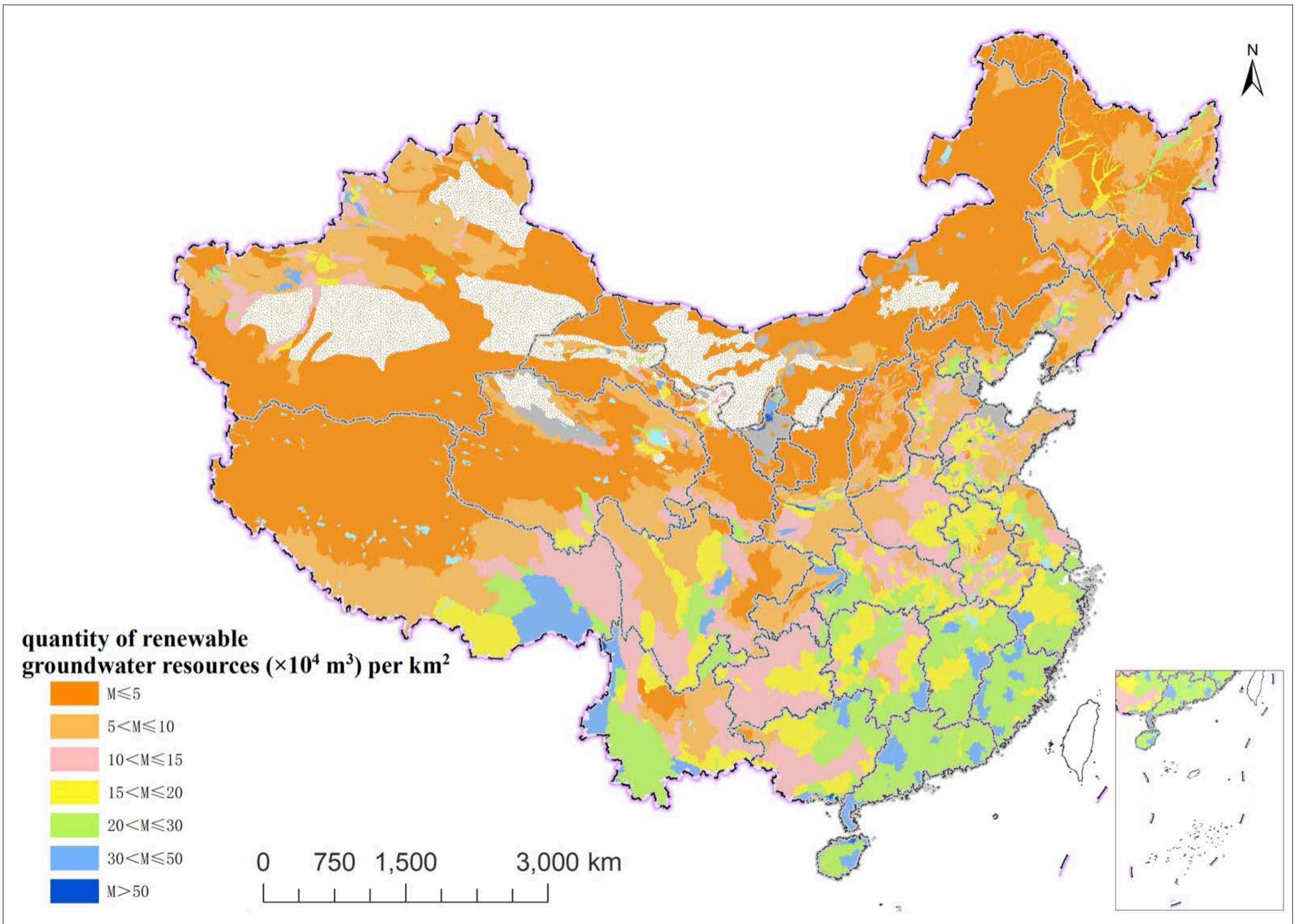


Figure 5-1 *The distribution of the quantity of renewable groundwater resources per km² in China (Source: Map by authors)*

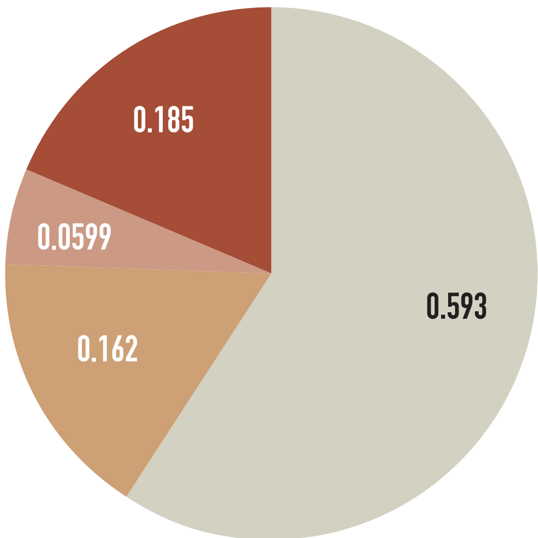
1.2. Groundwater Recharge

For plain areas, precipitation, infiltration recharge of rivers and lakes, and phreatic water supply from hilly areas provide natural recharge of shallow groundwater.
With the development of agriculture, there is an increasing water demand for irrigation that has become an important source of groundwater supply in some plain areas. For groundwater in hilly areas, precipitation is generally considered to be the only source of recharge. The annual amount of renewable groundwater resources in plain areas of China is 176.5 billion m^3, of which 59% comes from precipitation infiltration, 16% from the leakage of rivers and lakes, 6% from subsurface flow from hilly areas, and 18% from irrigation infiltration and other water supply sources (The General Institute of Water Resources and Hydropower Planning and Design, 2014). Groundwater recharge in plain areas in China is shown in Figure 5-2.

Due to the different climate and hydrological conditions in different areas, regionally the groundwater recharge is also quite different. The majority of groundwater in most areas of China derives from precipitation infiltration, which accounts for more than 70% of groundwater volumes. However, in the Northwest region, due to the influence of climate conditions, there is little precipitation, and more than 40% renewable groundwater resources are recharged by the leakage of rivers and lakes, and another 30% are recharged by irrigation water (The General Institute of Water Resources and Hydropower Planning and Design, 2014). The components of groundwater recharge in different regions of China are shown in Figure 5-3.

1.3. Exploitation and Utilization of Groundwater Resources

The historic development of groundwater exploitation and utilization of groundwater can be divided into six stages: the initial stage, the rising stage, the rapid expansion stage, the steady growth stage, the stable exploitation stage and the restricted exploitation stage (Figure 5-4). The initial stage was barely affected by the limited disturbance of human activity, thus the variation of the groundwater system was relatively small, and the functions of the groundwater system was very stable. The second stage indicated a rising tendency due to the impact of artificial groundwater exploitation, when that pressure is applied to a groundwater system, even though it was not notable, the total demand for groundwater increased slightly. Rapid expansion revealed a significant increase of groundwater exploitation and great pressure on the groundwater system that eventually resulted in a negative tipping point for groundwater services and functions. At the stage of steady growth, the groundwater system could hardly reach dynamic equilibrium of water quantity and water quality, and the amount of groundwater exploitation continuously rose until the peak value which caused the groundwater table to drop beyond its deepest limit, therefore it was difficult to give full play to the circulation and storage function of groundwater, and the ecological maintenance function and environmental geological function of the groundwater system had declined. The stable exploitation and restricted exploitation periods proved efforts have been made to scientifically manage and control groundwater



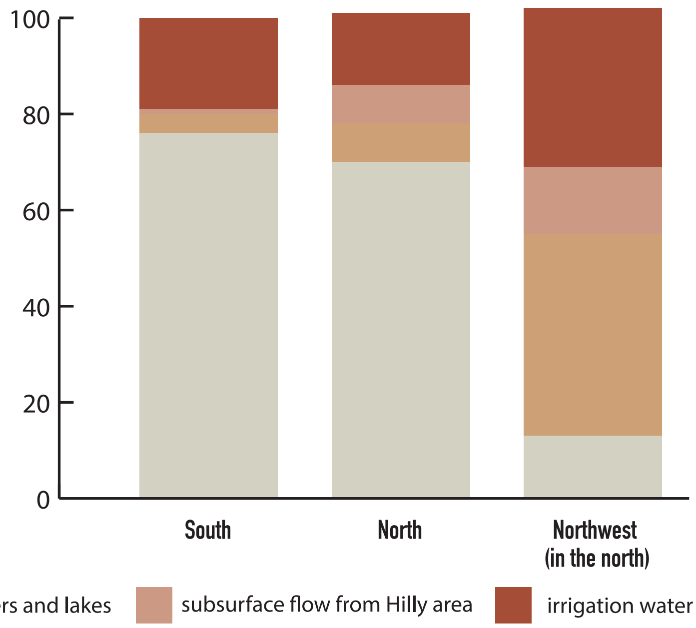


Figure 5-2 *Sources of renewable groundwater recharge (shallow groundwater) in plain areas in China (Source: Figure and graph by authors)*

Figure 5-3 *Components of renewable groundwater recharge in different regions in China (Source: Figure and graph by authors)* exploitation, therefore achieving optimal structure and function of the groundwater system (Xia & Zuo, 2018).

China's groundwater supply reached its maximum value around 2010, at more than 110 billion m^3 which accounted for 18% of the total water supply, particularly in some northern provinces where the groundwater supply reached over 50% of the total water supply. After 2010, due to the strict management and control of groundwater, groundwater exploitation showed a downward trend. In 2016, the quantity of groundwater exploitation was 107.3 billion m^3, making up 18% of the total water supply in China. The average quantity of groundwater exploitation per km^2 was around 11,000 m^3/km^2; however, 17% of counties had exploitation of more than 50,000m^3/km^2, mainly distributed in Sanjiang Plain, Liaohe Plain, North China, Inner Mongolia Plateau, Guanzhong Plain and the northern side of Tianshan Mountain (The General Institute of Water Resources and Hydropower Planning and Design, 2014) (Figure 5-5).

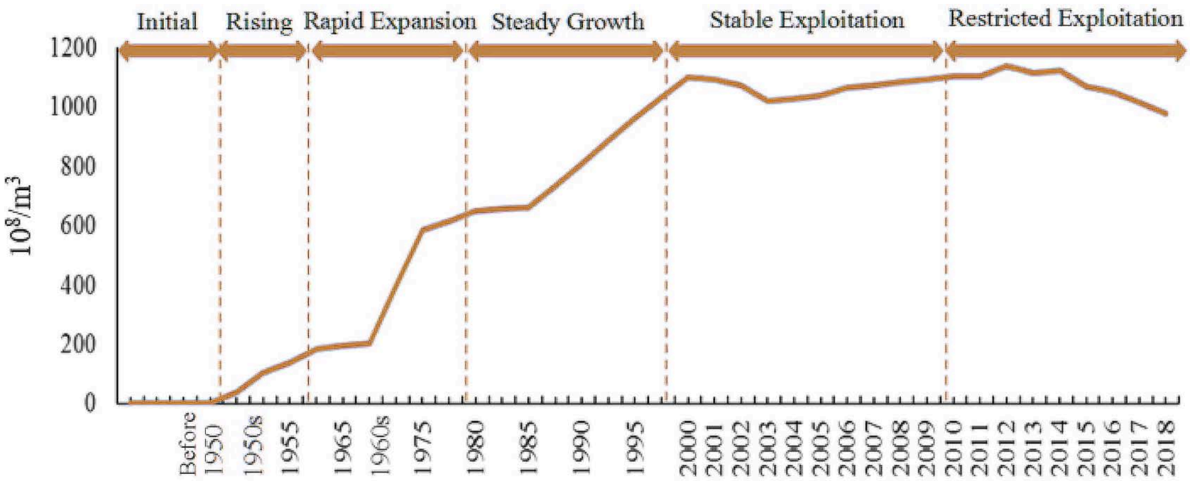


Figure 5-4 *Six stages of historic development of groundwater exploitation and utilization in China (Source: Figure and graph by authors)*

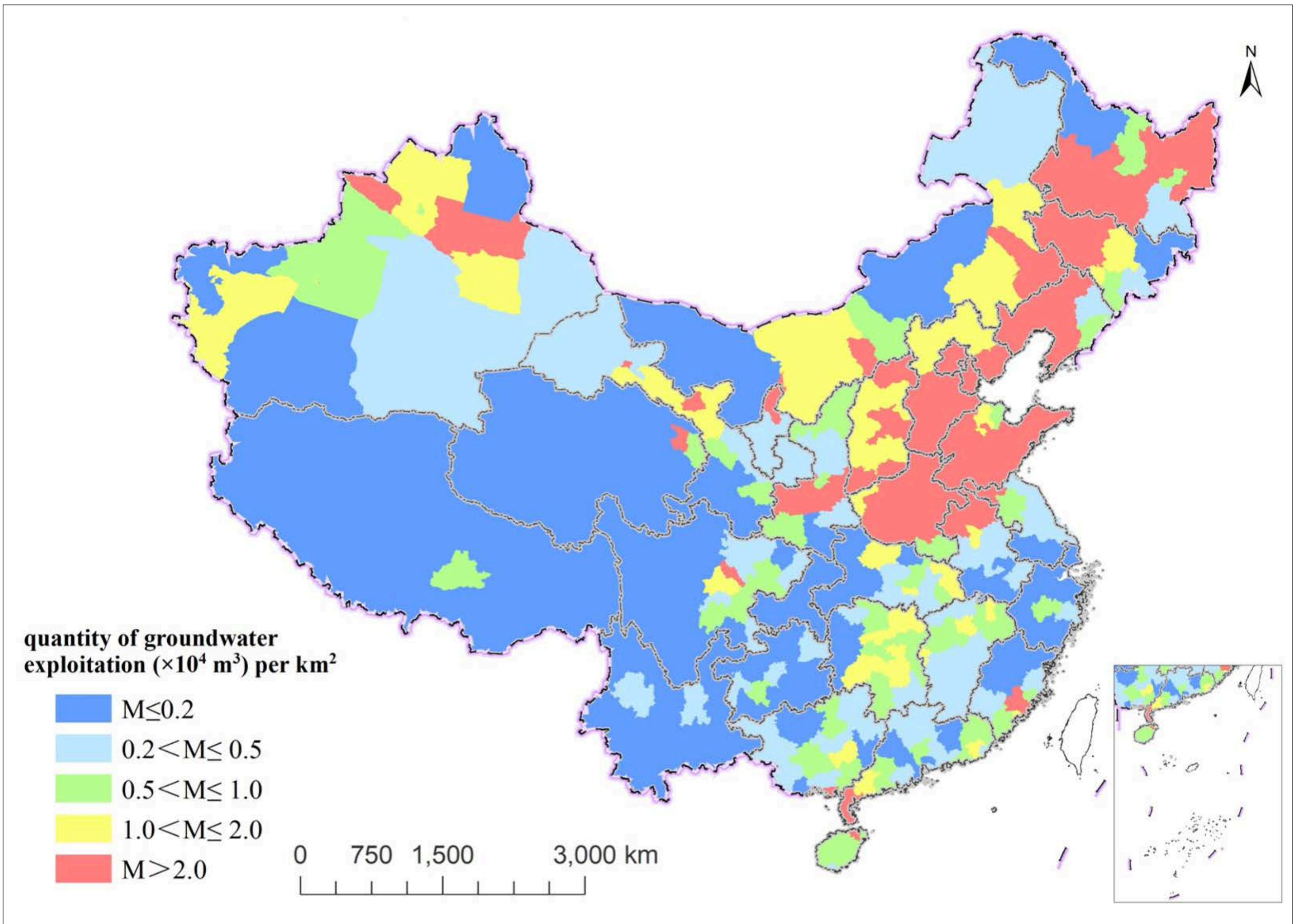


Figure 5-5 *The quantity of groundwater exploitation per km^2 in China (Source: Map by authors)*

1.4. Groundwater Functions

By analyzing the role of groundwater plays in the water cycle and the interaction between groundwater and related systems, there are four groundwater functions: circulation and reserve; maintenance of ecology; environment and geology; and resource supply.

- Circulation and reserve: groundwater is involved in the terrestrial water cycle, maintains the regeneration and renewal capacity of water resources, regulates the water circulation system and enhances the stability of the system through its own enormous circulation and reserve space. In general, 13% of the precipitation in China becomes groundwater resources, 81% of the groundwater resources are converted into surface water, forming 25% of the surface runoff; the remaining groundwater resources are consumed through phreatic evaporation and extraction, accounting for 4% of the total evaporation in China (The General Institute of Water Resources and Hydropower Planning and Design, 2014).

- Maintenance of ecology: groundwater maintains the water quantity balance, water-salt balance, water-heat balance of the ecological environment, and regulates the ecological hydrology. In some places, it is a key factor to maintain surface vegetation, lakes, wetlands and other ecosystems (Tang & Du, 2004). About 13% of the territorial area has been identified of great ecological importance in China. Ecosystems within the area are very sensitive to groundwater changes, including natural oases and their surrounding areas in arid and semi-arid areas, some wetlands and nature reserves (The General Institute of Water Resources and Hydropower Planning and Design, 2014).

- Environment and geology: groundwater is an important and particularly active geological agent, and the groundwater system plays a supporting and protecting role or effect on the stability of the geological environment. Groundwater over-exploitation may cause geological and environmental disasters, such as seawater intrusion, land subsidence and land fissures (Tang & Du, 2004; Tang *et al*., 2012).

- Resource supply: groundwater resources with certain conditions of recharge, reserve and renewal play a role in safeguarding the water supply. It can provide water supply for economic and social development, and groundwater resources can always be the reliable water supply during an emergency, e.g. when extreme drought occurs, or when surface water sources are polluted (Tang *et al*., 2012). Eighteen percent (18%) of the national water supply comes from groundwater, and the proportion of groundwater supply in Hebei province, Henan province and Inner Mongolia autonomous region accounts for more than 50% of the total water supply. In North China, 36% of agricultural water consumption comes from groundwater, and particularly, about 70% of agricultural water consumption in Beijing and Hebei province comes from groundwater (Zhang, Yang *et al*., 2006, The General Institute of Water Resources and Hydropower Planning and Design, 2014).

When the groundwater system is affected, some important functions of groundwater may be weakened. All problems caused by unreasonable exploitation of groundwater contribute to the degradation or loss of groundwater functions.

"All problems caused by unreasonable exploitation of groundwater contribute to the degradation or loss of groundwater functions"

02

Groundwater Functional Zones

2.1. System of Groundwater Functional Zones

According to regional groundwater natural resource attributes, ecological and environmental attributes, economic and social attributes, groundwater allocation for development and utilization, and the requirements of ecological and environmental protection, groundwater functional zones are divided into primary and secondary levels, so as to facilitate the management and supervision of groundwater resources by regional basin authorities and also the local water administrative departments (Yu *et al*., 2014; Wang *et al*., 2020).

The primary functional zones of groundwater are divided into three categories: protection zone, reserve zone and exploitation zone. They mainly reflect the interconnection between water use for economic and social development and ecological and environmental protection, therefore achieving the integrated national strategy for development, utilization and protection of groundwater resources. Within the primary level framework and based on their main functions, three categories are further divided into 8 secondary functional zones. The protection zone comprises an ecological fragile zone, geologically and environmentally sensitive zone, and groundwater conservation zone. The exploitation zone consists of a centralized water supply zone and distributed exploitation zone. The emergency water supply zone, water reserve zone and unsuitable exploitation zone are classified into a reserve zone (Table 5-1) (Yu *et al*., 2014).

2.2. Methodology for the Classification of Groundwater Functional Zones

The bases of classification are groundwater recharge conditions, hydrogeological conditions and extract conditions, groundwater quality, types of ecological and environmental systems and their protection requirements, current status of groundwater exploitation and utilization, and regional water resources allocation, etc. The specific conditions and characteristics of defining and classifying functional zones were referred to in Lv *et al*. (2007), Tang *et al*. (2012), Sun *et al*. (2014) and Yu *et al*. (2014).

2.2.1. Protection Zone

The protection zone has the ecological and environmental systems that are sensitive to a groundwater table, changes in water quality and groundwater exploitation. In the process of groundwater exploitation, the groundwater table should always be maintained above its ecological control table. The protection zone is further divided into three secondary zones including an ecological fragile zone, geologically and environmentally sensitive zone, and groundwater conservation zone.

(1) The ecological fragile zone applies where groundwater has great importance for ecological conservation and the ecological system is very sensitive to groundwater changes. Examples include essential wetlands, natural oases and their surrounding areas in arid and semi-arid regions, and important oasis corridors of ecological importance.

(2) The geologically and environmentally sensitive zone is found where a decrease in groundwater table would result in seawater intrusion, salt water intrusion, land subsidence, groundwater pollution and many other disasters as an effect of groundwater exploitation.

Table 5-1 *Classification of groundwater functional zones*

Primary	Secondary	Main Function
Protection Zone	Ecological fragile zone	Ecological maintenance
	Geologically and environmentally sensitive zone	Geology and environment
	Groundwater conservation zone	Circulation and reserve
Exploitation Zone	Centralized water supply zone	Centralized water supply for urban areas
	Distributed exploitation zone	Distributed water supply for rural areas
Reserve Zone	Emergency water supply zone	Emergency water supply
	Water reserve zone	Resources reserve
	Unsuitable exploitation zone	No particular functions

(3) The groundwater conservation zone is where groundwater exploitation and human activities are constrained in order to safeguard water and important spring water supply. The zone is mainly located in hilly areas. Vital springs, rivers with important ecological significance and riverside areas should also be categorized as groundwater conservation zones.

2.2.2. Exploitation Zone

The exploitation zone should satisfy the following conditions: good recharge and storage conditions. Usually, the pumping rate of a single well is no less than 10 m^3/h, the groundwater quality can meet the requirements of the relevant water users, and there is long standing demand for groundwater exploitation and utilization at present or in the near future. The exploitation zone could further split into another two secondary zones: centralized water supply zone and distributed exploitation zone.

(1) The centralized water supply zone is where the water output of a single well is no less than 30 m^3/h. This zone normally consists of centralized water supply for domestic water uses and industrial production water uses.

(2) The distributed exploitation zone is applied where at present or in the near future, groundwater is mainly exploited by distributed pumping wells for rural life, farmland irrigation and small rural industry. Except for centralized water supplies, the rest of the exploitation zone can be defined as a distributed exploitation zone.

2.2.3. Reserve Zone

A reserve zone can be designated where there is poor water quality, quantity and exploitation conditions, causing difficulty in exploitation and utilization. Even though there may be a certain potential for exploitation and utilization of water resources in some reserve zones, large-scale exploitation will not be scheduled in the near future. The reserve zone also consists of three secondary zones: unsuitable exploitation zone, water reserve zone and emergency water supply zone.

(1) The unsuitable exploitation zone is where the poor water quality and poor groundwater exploitation conditions cannot meet the requirements of water uses.

(2) The water reserve zone has good recharge and storage conditions, and there are few human activities at present or anticipated within a certain period of time. In some water reserve zones, the local surface water can meet the water demands, and there is no or only small scale groundwater exploitation.

(3) The emergency water supply zone has relatively good conditions for groundwater reserve, exploitation and water quality. It is generally prohibited for exploitation; water supply is provided only when emergencies or extreme drought occurs.

2.2.4. Classification Methods

With the concept of a protection zone, exploitation zone and reserve zone, one could easily judge whether a particular place should be classified as a protection zone, exploitation zone or reserve zone. But in order to conduct the zoning of groundwater resources at national level, a standard working procedure of classification is needed.

The classification of groundwater function can only be conducted within complete hydrogeological units and based on data collection and detailed investigation of groundwater resources for each area. Within a specific hydrogeological unit, the areas are divided by the intersected boundaries of a river basin and administrative area to form the basic units of groundwater functional zones.

The sequence of classification should be in accordance with the following principles:

(1) For the primary level, a protection zone needs to be clarified first, then an exploitation zone, followed by a reserve zone.

(2) For the secondary level of protection zone, the order should be ecological fragile zone, geologically and environmentally sensitive zone, and groundwater conservation zone is the last.

(3) For the secondary level of exploitation zone, first comes the centralized water supply zone and then the distributed exploitation zone.

(4) For the secondary level of reserve zone, an unsuitable exploitation zone shall be primarily defined, followed by an emergency water supply zone and water reserve zone.

“The groundwater quality can meet the requirements of the relevant water users, and there is long standing demand for groundwater exploitation and utilization at present or in the near future”

2.3. Classification Results

Following the classification methods above, each basic unit has been assigned a certain function, which covers the whole territory of China. The final classification results reflected a combination of national scale classifications and the results from basin or provincial level analyses (Cui *et al.*, 2013; Gao *et al.*, 2015; Liu *et al.*, 2018; Lv *et al.*, 2007; Tian *et al.*, 2016; Wang *et al.*, 2007; Wang *et al.*, 2020; Wang, 2018; Xiao *et al.*, 2017; Zhang *et al.*, 2006).

Table 5-2 *The Ratio of area of primary groundwater functional zones*

The primary groundwater functional zones	Plain area	Hilly area
Exploitation zone	44%	7%
Protection zone	17%	89%
Reserve zone	39%	4%

2.3.1. The Primary Groundwater Functional Zones

Sixty-seven percent (67%) of the land is protection zone, 18% is exploitation zone and the remaining 15% is reserve zone. For hilly areas, the protection zone accounts for 89%, the exploitation zone accounts for 7%, and the reserve zone is 4%. For plain areas, the exploitation zone takes up 44%, the protection zone is 17% and the reserve zone accounts for 39% (Table 5-2 and Figure 5-6).

2.3.2. The Secondary Groundwater Functional Zones

A total of 4,886 secondary functional zones for shallow groundwater are recognized across China, including 2,655 zones in hilly areas and 2,231 zones in plain areas. In the hilly areas, the groundwater conservation zone accounts for 74%, which is the most widely distributed secondary functional zone. In the plain area, the distributed exploitation zone and non-exploitation zone are the most predominant, taking up 43% and 31% of the plain area respectively. These classifications reflect that the plain area is the main area for groundwater exploitation and utilization. Except where there are centralized water supply zones in towns, industries and mining businesses, distributed exploitation is the main approach for groundwater exploitation. In addition, there is a large area of saline water in the plain area, which is classified as an unsuitable exploitation zone (Table 5-3 and Figure 5-7).

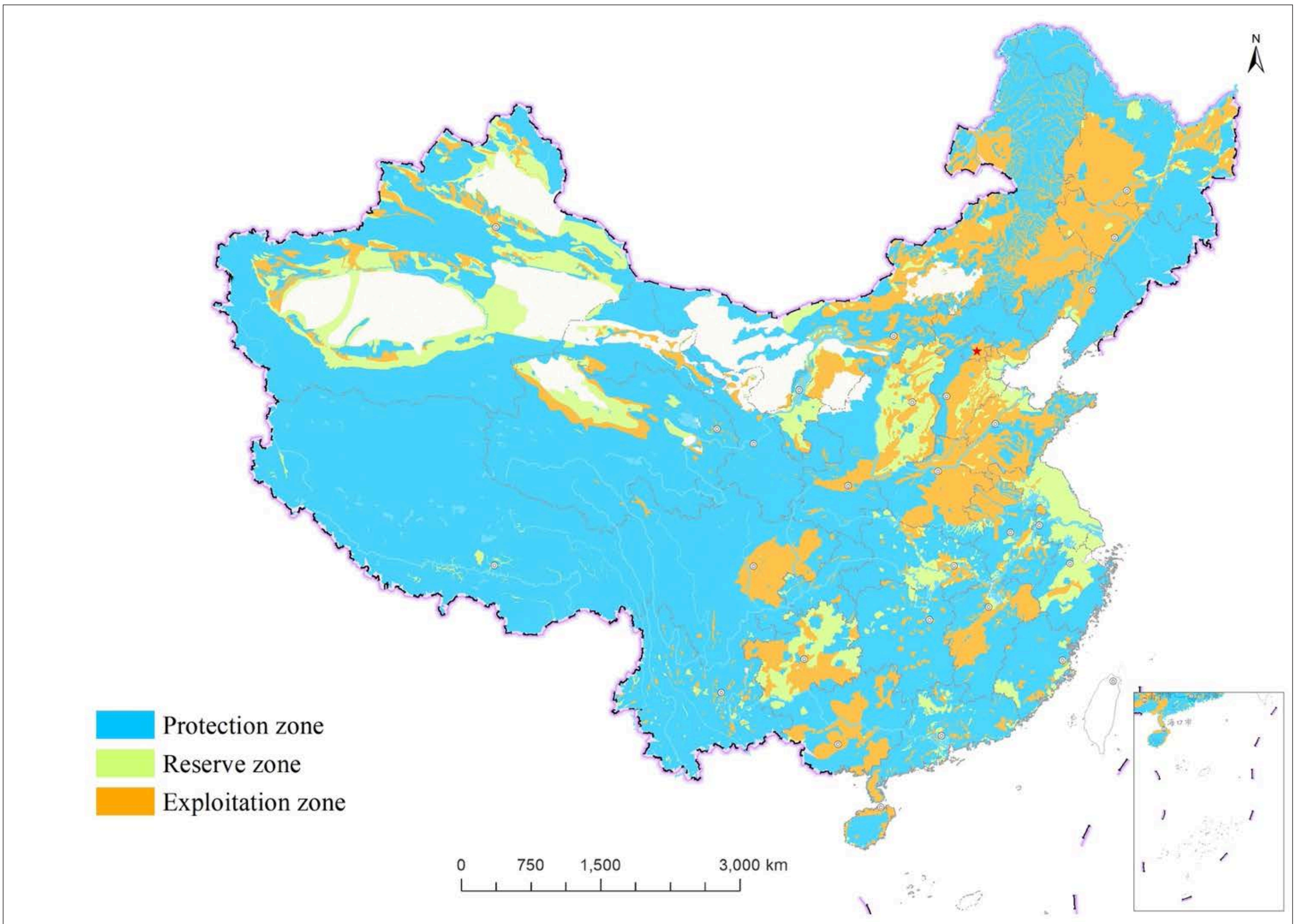


Figure 5-6 *The distribution map of the primary groundwater functional zones in China (Source: Map by authors)*

Table 5-3 The number and ratio of secondary groundwater functional zones in China.

The secondary groundwater functional zones	Nationwide					
	Plain area		Hilly area		Total	
	No.	Area	No.	Area	No.	Area
Centralized water supply zone	562	1.3%	312	0.6%	874	0.8%
Distributed exploitation zone	793	42.7%	440	6.4%	1233	17.5%
Ecological fragile zone	181	14.3%	266	15.4%	447	15.1%
Groundwater conservation zone	39	1.9%	1174	73.6%	1213	51.6%
Geologically & environmentally sensitive zone	76	0.9%	103	0.4%	179	0.6%
Unsuitable exploitation zone	354	31.1%	170	1.9%	524	10.8%
Water reserve zone	182	7.5%	135	1.3%	317	3.2%
Emergency water supply zone	44	0.2%	55	0.4%	99	0.3%
Total	**2231**	**100%**	**2655**	**100%**	**4886**	**100%**

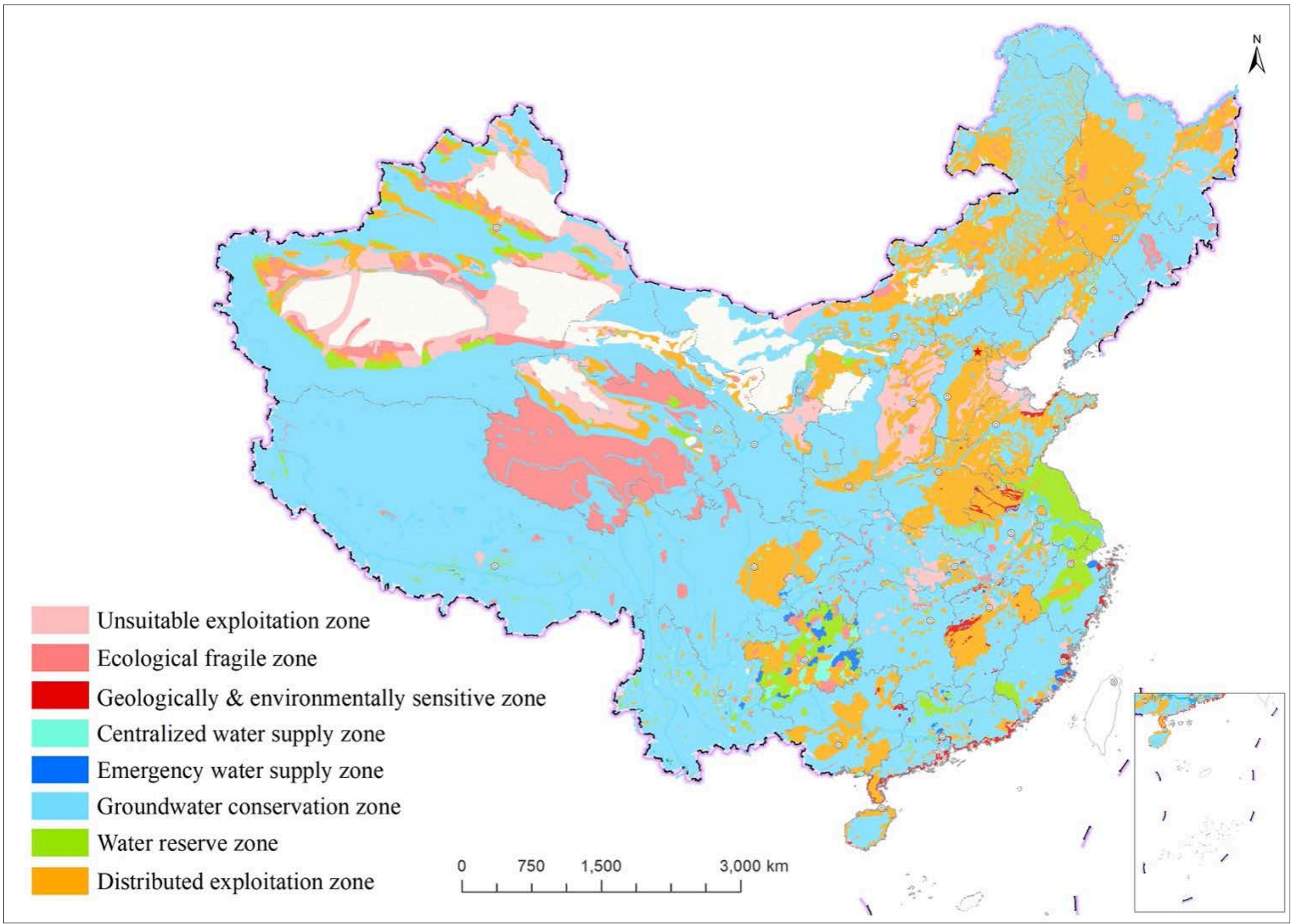


Figure 5-7 The distribution of the secondary groundwater functional zones in China (Source: Map by authors)

03

Analysis of Current Utilization Status of Groundwater Function Zones

Groundwater functional zones are classified according to the natural conditions and characteristics of regional groundwater, as featured by the natural characteristics of groundwater in one particular region, but do not reflect the current state of that zone. For example, some exploitation zones are already experiencing overexploitation problems, and even some areas classified as protection and reserve zones are still experiencing groundwater overexploitation issues. Therefore, groundwater management should rely both on the natural characteristics of groundwater and on the current state of exploitation and utilization. It is important to first identify the problems that have occurred so far and take appropriate measures accordingly.

3.1. The Current Exploitation Quantity in Groundwater Functional Zones

According to the China Water Resources Bulletin, groundwater exploitation for recent years in China is over 1,000 billion m^3. The primary exploitation zones cover about 20% of the country's area and take up about 25% of the country's groundwater resources, but the quantity of exploitation is more than 80%, and its secondary distributed exploitation zones contribute 70%. Distributed exploitation can be seen as the majority of the groundwater exploitation in China, mainly contributing to water supply in rural areas. The quantity of groundwater exploitation in different groundwater functional zones is shown in Table 5-4.

3.2. The Current Overexploitation Status in Groundwater Functional Zones

According to guidelines for the assessment of groundwater overexploitation zones (GB/T 34968-2017), plain areas can be regarded as having groundwater overexploitation problems if one of the following conditions exists: (1) The average annual exploitation in the region for many years is greater than its sustainable yield; (2) The water table in the groundwater exploitation zone shows a continuous decreasing trend due to groundwater exploitation, and the aquifer discharge exceeds the quantity of recharge; (3) Groundwater exploitation causes land subsidence, ground fissure, decrease in spring flow, seawater intrusion and other ecological, geological and environmental problems.

Table 5-4 The quantity of groundwater exploitation in groundwater functional zones in China

Primary	Secondary	Main Function
Protection Zone	Ecological fragile zone	2.6
	Geologically and environmentally sensitive zone	1.9
	Groundwater conservation zone	12.9
Exploitation Zone	Centralized water supply zone	11.2
	Distributed exploitation zone	75.5
Reserve Zone	Emergency water supply zone	0.2
	Water reserve zone	1.4
	Unsuitable exploitation zone	1.7
Total	/	**107.4**

Table 5-5 *Groundwater exploitation and utilization in groundwater functional zones*

Primary type	Secondary	Ratio of Resources Quantity %[1]	Ratio of Exploitation Quantity %[2]	No. of Overexploited Regions	No. of Near Overexploited Regions
Protection Zone	Ecological fragile zone	61	12%	14	25
	Geologically and environmentally sensitive zone	2	2%	17	4
	Groundwater conservation zone	5%	2%	48	13
Reserve Zone	Unsuitable exploitation zone	3%	2%	49	28
	Water reserve zone	5%	1%	19	4
	Emergency water supply zone	1%	0%	5	/
Exploitation Zone	Distributed exploitation zone	21%	70%	181	62
	Centralized water supply zone	2%	10%	189	69
Total	/			**522**	**205**

1 The ratio of renewable groundwater resources quantity in groundwater functional zones to the national renewable groundwater resources quantity
2 The ratio of groundwater exploitation quantity in groundwater functional zones to the national groundwater exploitation quantity

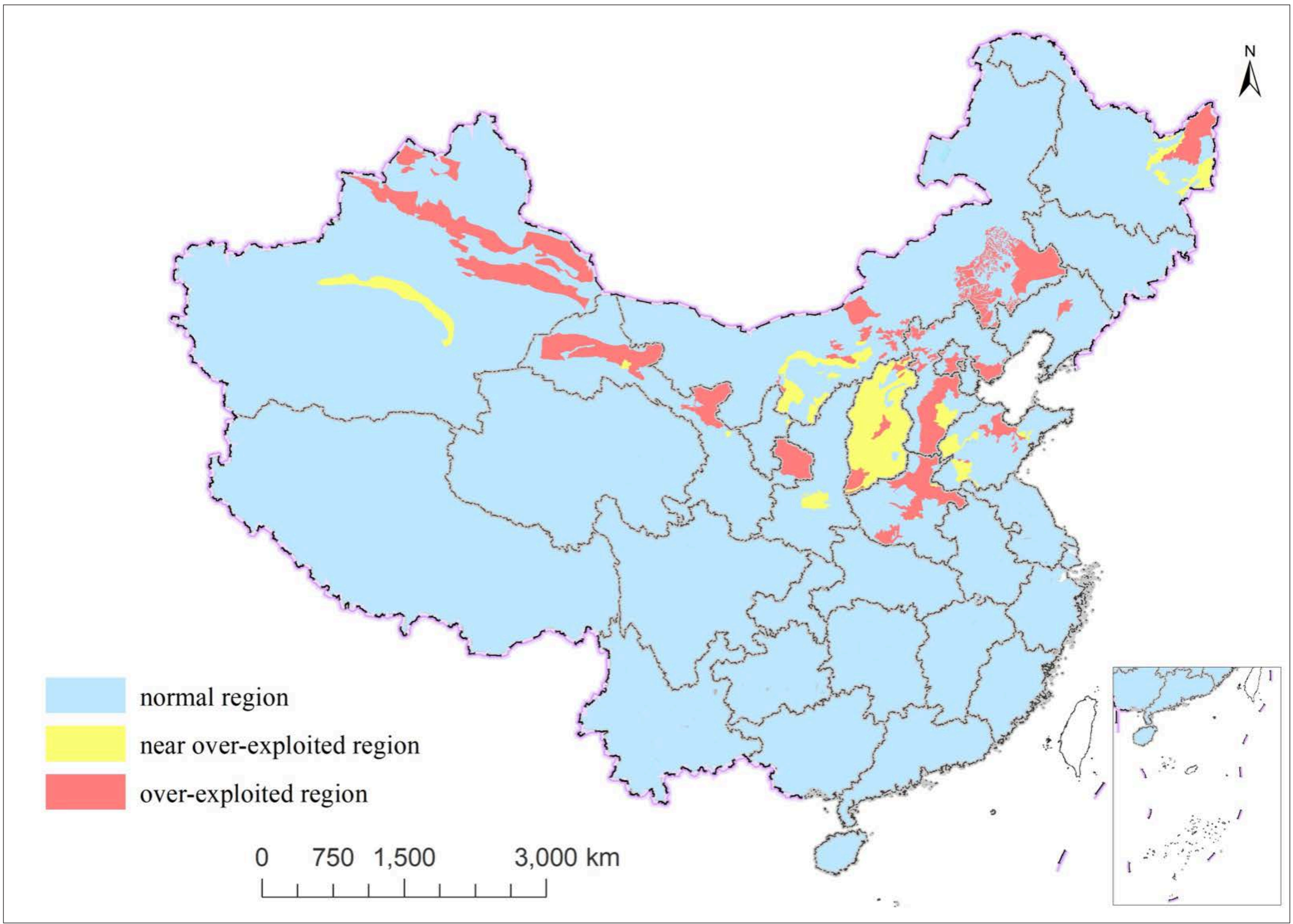


Figure 5-8 *The distribution of the extent of groundwater exploitation and utilization in groundwater functional zones (Source: Map by authors)*

For hill areas, there is still no widely accepted method to target the overexploitation zone. But for the purpose of ecological protection, hilly areas can be regarded as having groundwater overexploitation problems if one of the following conditions exists: (1) The water table in the groundwater exploitation zone shows a continuous decreasing trend due to groundwater exploitation; (2) The river base flow or surface runoff significantly declines due to groundwater exploitation.

Based on the above standards and criteria, analysis indicates that a total of 10% of the number of functional zones have problems of groundwater overexploitation in plain areas, and 1% of functional zones have problems of unreasonable groundwater exploitation and utilization in hilly areas. In addition, 4% of groundwater functional zones are near overexploitation (Table 5-5 & Figure 5-8), meaning that although the quantity of groundwater exploitation is less than the sustainable yield, withdrawal reaches more than 90% of the sustainable yield.

“It is necessary to reduce the influences of human activities, to maintain a basic equilibrium in groundwater systems under changing conditions, and to bring the water quantity and water table within a reasonable threshold range”

04

Countermeasures for the Management and Control of Groundwater Functional Zones

4.1. Overall Framework of Groundwater Management and Control

The overall framework of management and control of groundwater exploitation and utilization is to take groundwater as a hard constraint to economic and social development. It is necessary to reduce the influences of human activities, to maintain a basic equilibrium in groundwater systems under changing conditions, and to bring the water quantity and water table within a reasonable threshold range. Under the premise of ensuring the good function of groundwater recycling and reserve, as well as ecological maintenance and geological stability, groundwater should play a role in water resource supply, meet current water demands and keep sufficient strategic reserves. In a word, it can be summarized as a “four-level progressive” management and control approach, as elaborated below.

The first level is to maintain the beneficent water cycle and maintain the natural discharge of groundwater, such as river discharge and phreatic evaporation, so as to maintain the interaction between groundwater, atmospheric water and surface water. Second is the balance between the needs of humans and nature. Groundwater exploitation should meet the needs of groundwater in wetlands, natural oases in arid areas, important spring areas and other ecological systems, as well as for the prevention and control of geological disasters. The third is to balance humans’ daily demand and exceptional demand for groundwater, therefore reserving the available water supply for the needs of natural disaster or water pollution and other special circumstances, as well as any unforeseen demand for future development. The last is to optimize the use and control of groundwater, and reasonably allocate the available groundwater resources for human daily use among different industries. High-quality groundwater is given priority for domestic water uses in urban and rural areas in order to achieve the optimal use of groundwater.

4.2. The Management and Control of Groundwater Functional Zones

Groundwater functional zones are viewed as a fundamental concept for groundwater management. There are some specific management and control indicators that should be formulated for groundwater functional zones, including control indicators of groundwater exploitation and the groundwater table.

4.2.1. Control Indicators of Groundwater Exploitation

Generally speaking, groundwater exploitation control in plain areas should adhere to the principles of stabilizing the balance of groundwater recharge and discharge, maintaining the beneficent water cycle, meeting the water demand for the natural environment, retaining sufficient strategic reserves and making efficient groundwater uses. Considering the difference between groundwater exploitation and recharge patterns, a portion of groundwater will inevitably be consumed in drainage and evaporation. Regional groundwater exploitation should not exceed 90% of the total recharge. The sustainable yield in ecological fragile zones and coastal zones should not exceed 50% of the total recharge. Groundwater exploitation in hilly areas may reduce river baseflows, causing reduction in surface water flows. Thus, groundwater exploitation in hilly areas should also consider surface water exploitation in order not to cause significant decline in surface runoff.

However, considering groundwater has already been overexploited in some areas, in the future, management and control strategies should be developed based on the requirements of the sustainable yield as well as the needs of governing current issues. Detailed measures aimed at different zones are explained as following.

(1) For any groundwater functional zones that already have a problem with groundwater overexploitation, new groundwater exploitation should be prohibited. For the permitted quantity of exploitation, measures such as water saving, replacing groundwater exploitation by surface water, reducing the area with high water-consuming crops, and even fallowing shall be taken to gradually reduce groundwater exploitation, manage groundwater overexploitation, and recharge the historical deficit in water recharge.

(2) For any groundwater functional zones that are near groundwater overexploitation, and do not have further exploitation and utilization potential, the current status shall be maintained and no additional new groundwater exploitation will be permitted in the future. If conditions allow, some zones can take some measures to reduce groundwater exploitation, therefore reserving groundwater resources.

(3) For any exploitation zone without overexploitation problems, the groundwater exploitation can be appropriately increased according to the demand of social and economic development, therefore providing high-quality water resources for human beings.

(4) Any protection zone without overexploitation problems should prioritize the concept of protection and basically maintain the current status of the groundwater exploitation and utilization. There is no need to create new groundwater exploitation, except in cases of real need, where small-scale and distributed exploitation under strict controls can proceed, but only for drinking water.

(5) Any reserve zone without overexploitation problems should not increase massive groundwater supply for daily uses, while groundwater supply could be applied if in urgent need.

Table 5-6 Standard for control indicators of groundwater table

Functional Zones		Maximum Depth	Minimum Depth
Exploitation Zone		✓ No continuous decline in groundwater table ✓ Effective groundwater supply ✓ Maintenance of groundwater inflow per unit	✓ Reduction in the ineffective phreatic evaporation ✓ Maintenance of reserve space ✓ Prevention of groundwater pollution
Protection Zone	Ecological fragile zone	✓ Maintenance of the rising height of capillary water to the depth of root system in soil ✓ Maintenance of surface vegetation	✓ Prevention of groundwater pollution
	Geologically and environmentally sensitive zone	✓ Prevention and control of land subsidence, seawater intrusion, land subsidence and other environmental geological disasters	✓ Prevention of groundwater pollution ✓ Prevention of soil salinization
	Groundwater conservation zone	✓ Maintenance of river base flow and spring discharge, etc.	✓ Prevention of groundwater pollution
Reserve Zone		/	/

4.2.2. Control Indicators of Groundwater Table

The control of groundwater table depth should consider the range of dynamic changes in the groundwater table. The groundwater table within this range can maintain a beneficent water cycle and meet the conditions that support the ecological and geological environment. Usually, the maximum depth of groundwater table should be maintained above the critical depth of phreatic evaporation and surface water discharge to rivers and lakes (generally 4 m). The maximum depth of groundwater table is determined to maintain the flexibility of groundwater reserve space for groundwater discharge and recharge, prevent soil salinization and should be deeper than where pollutants can reach. For wetlands or marshy areas, groundwater table depth should be less than 1 meter. For oases in arid areas, groundwater table depth should above the depth of vegetation roots plus the height of capillary rise. For areas that are prone to geological disaster, the groundwater table should above the critical depth of land subsidence, seawater intrusion, land collapse and other geological disasters. For areas that have important buildings in the region, groundwater table depth should be below the designed protection depth for urban building foundations. Standards for control indicators of groundwater tables in different groundwater functional zones are summarized in Table 5-6 (Yu *et al*., 2014).

Currently, groundwater overexploitation exists in many areas and the groundwater table is much deeper than the desirable standard. Control indicators of groundwater tables at different stages should be determined based on the current status of each groundwater table and the progress on governance and protection of groundwater from overexploitation.

The groundwater table at any given time is the cumulative result of changes in groundwater table over a period of time. Therefore in the future, when determining the control indicators of groundwater tables in a specific year, the calculations need to measure the annual differences of a groundwater table from present to the targeted year.

05

Conclusion

(1) Groundwater is widely distributed in China and its management is supported by a zonation process which is designed to guide groundwater utilization and ecological and environmental protection. The process geographically separates groundwater resources and the related landscape into 3 primary functional zones (which are protection zone, exploitation zone and reserve zone), and 8 secondary functional zones.

(2) The classification of groundwater function is based on the division of a basic unit. Following the principle and sequence of classification, each basic unit could be assigned a certain groundwater function, which covers the whole territory of China. Sixty-seven percent (67%) of the land is protection zone, 18% is exploitation zone and the remaining 15% is reserve zone. For hilly areas, the protection zone accounts for 89%, the exploitation zone accounts for 7%, the reserve zone is 4%. For plain areas, the exploitation zone takes up 44%, the protection zone is 17% and the reserve zone accounts for 39%.

(3) The current state of exploitation and utilization for each functional zone has been analyzed in this paper so as to identify the problems that have occurred so far.
The groundwater exploitation for recent years in China is over 1,000 billion m^3. The primary exploitation zones cover about 20% of the country's area and take up about 25% of the country's groundwater resources, but the quantity of exploitation is more than 80%, and its secondary distributed exploitation zones contributes 70%. A total of 10% of the number of functional zones have problems of groundwater overexploitation in plain areas, and 1% of functional zones have problems of unreasonable groundwater exploitation and utilization in hilly areas. In addition, 4% of groundwater functional zones are near overexploitation.

(4) Based on the methods, and the results of groundwater analysis, there are a few proposals and suggestions for groundwater protection and management presented in this paper. An overall framework of management and control of groundwater exploitation and utilization was developed, which takes groundwater as a rigid constraint to economic and social development. Accordingly, as the management and governance objectives, a set of control indicators of groundwater management in functional zones has been formulated including control indicators of groundwater exploitation and groundwater table. Targeted on the gap between the current status of groundwater system and the protection objectives, optimal and feasible solutions could be proposed and implemented.

References

Cui, C. Y., Yang, L. B. & Liu, J. (2013).
Control scheme of groundwater exploitation in the Yellow River Basin. *Yellow River*, 1, pp. 91-92, 103.

Gao, S., Tang, Y., Wang, H. L. & Wang, L. (2015).
Research on the classification of groundwater functional zones in Songliao Basin of Inner Mongolia.
Journal of China Institute Water Resources and Hydropower Research, 2, pp. 117-123.

Guidelines for the assessment of groundwater overexploitation zones (GB/T34968-2017).
General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China and Standardization Administration, Beijing.

Liu, J. F., Li, S., Ren, C. Y., Wang, Z. M. & Zhang, B. (2018).
Research on the classification of groundwater functional areas in Jilin Province.
Journal of Arid Land Resources and Environment, 7, pp. 159-165.

Lv, H., Du, Z. D. & Wang, J. (2007).
Preliminary study on groundwater functional zones in Shandong Province. *Journal of Hydrology*, 27(3), pp. 75-77.

Sun, J. W., Liu, P. B. & Li, G. M. (2014). Study on the methods of categorizing groundwater functional zones. *Yellow River*, 4, pp. 44-46.

Tang, K. W. & Du, Q. (2004). Classification of groundwater functional Zones. Journal of Water Resources Protection, 5, pp. 16-19.

Tang, K. W., Tang Y., Li, Y. Y. & Hou, J. (2012).
The system of groundwater functional zones and its application. *Journal of Hydraulic Engineering*, 11, pp. 1349-1356.

The General Institute of Water Resources and Hydropower Planning and Design. (2014).
Investigation and assessment of water resources development and utilization in China. Beijing, China: Water Pub.

The Ministry of Water Resouces of China. (2001~2019). China Water Resources Bulletin. Beijing: Water Pub.

Tian, W. Y. (2016). Division method and practice of groundwater functional areas in Liaoning Province.
Journal of Water Resources & Hydropower of Northeast China, 34(05), pp. 33-34.

Wang, G. L., Chen, D. H., Lin, W. J., Fan, Q. & Zhang, W. (2007).
Rational development and protection of groundwater resources in Northern China. *Journal of Chinese desert*, 04, pp. 684-689.

Wang, J. Z., Zhang, G. H., Cui, H. H., Wang, Q., Dong, H. B. & Hao, J. (2020).
Characteristics and application of suitable system indicators for groundwater functional zones in Northwest China.
Journal of Hydraulic Engineering, 7, pp. 796-804.

Wang, Y. H. (2018). Study on the methods and results of categorizing groundwater functional zones in Shanxi Province.
Soil and Water Conservation Science and Technology in Shanxi, 3, pp. 7-9.

Xia, J. & Zuo, Q. T. (2018). 40 years of water resources utilization and protection in China (1978-2018).
Journal of Urban and Environmental Research, 2, pp. 18-32.

Xiao, P., Yu, W., Hu, G. M. & Zhao, X. Y. Z. (2017).
Evaluation and classification of groundwater functions in Jianghan-Dongting Plain. *Yangtze River*, 1, pp. 6-11, 19.

Yu, L. L, Tang, K. W., Hou, J. & Yang, Y. (2014).
The protection and management of groundwater functional zones. *China Water Resources*, 3, pp. 39-42.

Zhang, G. H., Shen, J. M., Nie, Z. L., *et al*. (2006).
Evaluation theory and method for regional groundwater function and sustainable groundwater utilization.
Journal of Hydrogeology and Engineering Geology, 4, pp. 62-66.

Zhang, G. H., Yang, L. Z, Nie, Z. L., *et al*. (2006).
Characteristics and evaluation of groundwater functions in North China Plain. *Resources Science*, 31(3), pp. 268-374.

III

Tools for Analysis

©astudio/Shutterstock

6

The Golden Gift of Groundwater in Australia's MDB

David Adamson, Christopher Auricht and Adam Loch

David Adamson, Center for Global Food and Resources, The University of Adelaide, SA, Australia.
e-mail: david.adamson@adelaide.edu.au
Christopher Auricht, School of Agriculture, Food and Wine, The University of Adelaide and Auricht Projects, Adelaide SA, Australia.
e-mail: chris@auricht.com
Adam Loch, Center for Global Food and Resources, The University of Adelaide, SA, Australia.
e-mail: adam.loch@adelaide.edu.au

Abstract

The Murray-Darling Basin (MDB) has the second-most variable surface flows in the world. The unreliable nature of MDB surface water supply is expected to increase under climate change. To partially address this future problem, Australia's government released 927 gigalitres (GL = 1 billion litres) of groundwater rights to agricultural users in the basin under the Murray-Darling Basin Plan (2012-2026). A key argument for that action was the perception that groundwater resources in the basin are sustainable, and more reliable, than surface water resources. Access to more reliable water often transforms agricultural cropping choices.
This chapter uses an optimization model of the MDB to explore how basin agriculture may transform in response to reliable water access—particularly in the northern part of the MDB. We find that traditional opportunistic cropping systems (i.e., annuals) shift towards high-value systems (e.g., perennials) and change irrigation practices when access to groundwater resources is increased. We also examine the change in value for those new groundwater rights as climate change impacts take hold.

Keywords

Conjunctive water resources, risk and uncertainty, transformation, reliability of rights, water rights

01

The Murray-Darling Basin Plan

This chapter explores the implications from increased access by agricultural producers in Australia to groundwater resources. Increased access will change the both the production systems (i.e., irrigated commodities) and management systems (i.e., irrigation practices) and our objective is to model how production and management transformations occur in response to both increased groundwater resource access and future climate change impacts to surface water supply. Australia's Murray-Darling Basin (MDB) provides the context for our analysis.

Australia's MDB can be divided into two parts, the highly developed and connected southern basin (SMDB) and the underdeveloped northern basin (NMDB) as shown in Figure 6-1. Water flows through the NMDB into the SMDB, and then runs from the eastern mountain ranges across western plainlands where much of the agricultural production takes place. The terminal node for the Murray River is the Coorong wetlands, located in South Australia (south of Adelaide in Figure 6-1).

'Development and connectivity' describe the extensive capital works (i.e. dams, irrigation networks and other capital investments) that help to reduce the surface water supply variability. These are required because the MDB has the second most variable surface water runoff globally (Love, 2005), punctuated by periodic flood events and extensive severe droughts. Of the total 21,000 gigalitres (GL = one billion litres or 810.7 acre feet) of surface water storage in the MDB, around 77% is situated in the southern basin (MDBA, 2020a). Greater access to stored surface water means that southern agriculture enjoys higher supply reliability compared to growers located in the NMDB. As Loch *et al.* (2020a) discuss, reliability is important for determining crop choices because the ability to irrigate perennial crops annually is necessary to preserve the capital invested. Higher surface water reliability

Figure 6-1 *Location of key rivers, supply sources and critical identifiers for the MDB (Source: https://www.mdba.gov.au/sites/default/files/images/pubs/Murray-Darling_Basin_Boundary.jpg)*

Table 6-1 2012 MDB Plan and Change in Water Resources (GL)

k	Catchment	Trading Zone	Net Change in Volume	
			Ground water	Surface Water
k1	Condamine	NMDB	62.8	-60.0
k2	Border Rivers QLD	NMDB	47.8	-8.0
k3	Warrego Paroo	NMDB	132.0	-9.0
k4	Namoi	NMDB	0.0	-10.0
k5	Central West	NMDB	8.6	-65.0
k6	Maranoa Balonne	NMDB	41.9	-40.0
k7	Border Rivers Gwydir	NMDB	128.7	-49.0
k8	Western	NMDB	95.5	-6.0
k9	Lachlan	Unconnected	123.3	-48.0
k10	Murrumbidgee	Southern NSW	0.0	-320.0
k11	North East	Southern VIC	0.0	-32.9
k12	Murray 1	Southern NSW	0.1	-7.9
k13	Goulburn Broken	Southern VIC	32.3	-369.3
k14	Murray 2	Southern NSW	1.3	-131.0
k15	North Central	Southern VIC	0.0	-194.5
k16	Murray 3	Southern NSW	1.1	-117.9
k17	Mallee	Southern VIC	142.7	-30.4
k18	Lower Murray Darling	Southern NSW	0.1	-13.2
k19	SA MDB	Southern SA	111.3	-101.0
		TOTAL	**929.2**	**-1,613.0**
	Further Reduction of Surface water by Trading Zones			
	Northern			-143.0
	Southern NSW			-462.9
	Southern VIC			-425.3
	Southern SA			-82.8
	Southern All			-450.0
	Reduction in the Trading Zones			-1,564.0
	TOTAL Surface Water Reductions*			**-3,194.0**
	TOTAL Net Change (Ground + Surface)			**-2,265.0**

has also encouraged different irrigated agriculture producers to develop across the two basins.

The NMDB has developed opportunistic agricultural production comprised of annual crops produced only when water is available (e.g., cotton). Alternatively, SMDB agricultural production includes both annual and perennial cropping systems (e.g., almonds); where perennial producers often own surface water rights with high reliability that receive 95-100% of their full water allocation annually. Other surface water rights include general reliability (receive ~30% of their allocation on average), and supplementary/low reliability rights (receive water during river pulse flow events derived from high rainfall/flooding).

A threat to the future reliability characteristics of water supply in the MDB is climate change which is expected to reduce surface water runoff (Chiew *et al*., 2008). Like many river basins globally, water rights in the MDB have also been over-allocated, reducing the reliability and value of water resources for all users, and resulting in net welfare losses where environmental assets are impacted (i.e. negative externalities). For example, a lack of surface flows may result in black-water events from deoxygenated water, increased salinity, blue-green algal outbreaks and soil acidification—where any one of these events will reduce species diversity, river system connectivity and morphology, and/or loss of key riverine habitat. In 2007 the Australian federal government sought to address all of these issues with the introduction of a Water Act (Commonwealth of Australia, 2008). The Water Act was created to ensure a single planning mechanism for the MDB focused on establishing, and achieving, sustainable levels of extraction.

In 2012, the Murray-Darling Basin Plan (MDB Plan) was enacted and regulators estimated that between 2,750-3,200 GL of surface water would need to be recovered from irrigators and transferred to an environmental manger to achieve a sustainable diversion limit (SDL) going forward (MDBA, 2012). An SDL is a reduction in the total volume of water that was originally extracted for irrigated agriculture (i.e., the current diversion limit or CDL which sets a baseline for reduction assessments), with that reduction transferring to environmental uses. That is, the total volume of extraction does not lower, but the proportion of use between users is altered such that sustainable objectives can be achieved.

To achieve that water reduction, over AU$13 billion was allocated across two main programs. The first (Restoring the Balance) focused on buying back rights from willing sellers while the second (Sustainable Rural Water Use Infrastructure Program) invested in water efficient technology savings. Any water recovered under either of these programs enables actual resources to be transferred to an environment manager for national welfare gains (Adamson & Loch, 2018). These programs are well documented elsewhere (Mallawaarachchi *et al.*, 2020).

“Any increase in access to groundwater resources must stem from a belief they represent a highly reliable resource”

However, what is less known about the MDB Plan is that an additional 927 GL of groundwater reserves above previous extraction limits were released for agricultural use. Around 45% of these new groundwater resources are located in the NMDB (see Table 6-1), with an additional 13% in the Lachlan catchment—which for the purposes of this chapter we will consider part of the NMDB. Table 6-1 highlights the MDB Plan's proposed net changes in water by all 19 catchments in the MDB (see section 3.2). As shown, these catchments are also categorized into NMDB, the unconnected Lachlan catchment, and SMDB catchments across the three state jurisdictions (called Trading Zones in Table 6-1, and where refer to individual catchments within the MDB across New South Wales (NSW), Victoria (VIC) and South Australia (SA)). Also provided is the additional surface water that needs to be recovered by trading region to achieve a net reduction of 3,194 GL in surface water.

Given the MDB Plan was created to achieve sustainable extractions under an expectation of highly variable water resources in future due to climate change impacts, we argue that any increase in access to groundwater resources must stem from a belief they represent a highly reliable resource. We base this on the counter-factual that, under any adoption of a precautionary principle approach, water regulators would not release these resources if there was any doubt as to their reliability both now and into the future. If we accept the assumption that groundwater is perceived by regulators in the MDB—and water users in agriculture—as a highly reliable resource, what might this mean for agricultural production and management transformation across the Basin? Further, what changes might we see in the value of surface and groundwater resources as climate change impacts increase, how could the risk profile surrounding cropping patterns change, and what also might this mean for future water resource management? To answer these questions, we first extend the discussion on groundwater and resource reliability. Next, the methodology and model used to explore these issues are presented. Finally, the results from the analysis are discussed before concluding comments are made.

02

Water Supply in the MDB

2.1. Overview of Resources

Prior to the MDB Plan, total average annual conjunctive water supply in the MDB was believed to be 26,418 GL. Runoff from rainfall is the largest contributor accounting for 22,925 GL (Mallawaarachchi *et al.*, 2010). Groundwater extractions account for 2,373 GL (MDBA, 2012) and 1,118 GL of water is transferred into the MDB from the Snowy River Hydro Scheme as shown in Figure 6-1 (Murray-Darling Basin Commission, 2006). In any given year, if supply exists, approximately 15,716 GL of water (13,344 GL of surface water and 2,372 GL of groundwater) can be allocated to irrigation/environmental users and for essential human water use (e.g., 206 GL for The City of Adelaide) in the MDB (Adamson *et al.*, 2011).

Table 6-2 CDL Entitlements by Catchment (K)

k	Entitlement Security (GL)				Total
	Ground	High	General	Supplementary	
k1	132			1,398	1,530
k2	24			587	611
k3	2			125	127
k4	224	5	286	255	770
k5	99	18	632	143	892
k6	88			932	1,020
k7	108	16	773	375	1,272
k8	79			196	275
k9	393	31	615	68	1,107
k10	355	377	1,888	697	3,317
k11	0	196	79	61	336
k12	6	6	50	20	82
k13	486	1,221	706	139	2,552
k14	96	96	834	334	1,360
k15	0	913	432	161	1,506
k16	87	86	750	301	1,224
k17	70	156	73	12	311
k18	4	11	111	275	401
k19	120	449	0	0	569
Total	**2,373**	**3,582**	**7,230**	**6,081**	**19,266**

However, due to its variability, the use of average numbers provides misleading estimations of water supply reliability in the MDB. Water resources in the MDB are allocated from the surface water storages (Young & McColl, 2009), and the classification of surface water rights into three classes (high, general and supplementary) means that water is only allocated when it is available. See Table 6-2 which shows where the three surface rights and one groundwater right are located.

As evident in Figure 6-2, surface water diversions from river systems for agricultural production have ranged from around 10,000 GL to only 3,000 GL in 2007-08 during the Millennium Drought; which occurred between 2001 and 2010 (Heberger, 2011). Demand for greater water withdrawal in the MDB is always present though, and under an expectation that climate change is expected to reduce future reliability of water, any additional access to reliable groundwater will provide opportunities for all advantaged users (e.g., urban and environmental users). However, for simplicity in this chapter we assume that all water is only used by irrigators for agricultural production.

2.2. Groundwater Resources

Groundwater reserves have the capacity to mitigate water supply variability due to the spatial disaggregation between recharge area and consumption (Kirby *et al.*, 2014). Provided that aquifers are managed carefully, groundwater is considered a renewable resource (Crosbie *et al.*, 2008; Loáiciga, 2003). However, unsuitable consumption will compromise the aquifer structure reducing its ability to recharge (Brunke & Gonser, 1997), the volume that can be stored (Scanlon *et al*., 2012), and water quality can also be degraded (Knapp & Baerenklau, 2006).

Irrigators in the NMDB access groundwater from the Great Artesian Basin (GAB), whose recharge zone includes the Gulf of Carpentaria in northern Queensland (Smerdon *et al.*, 2012). The NMDB is thus largely comprised of fractured or fissured aquifers of low to moderate productivity. The SMDB enjoys relatively higher productivity aquifers as shown in Figure 6-3.

In general, groundwater quality in the MDB is mixed but total resource suitability for irrigation is generally considered to be

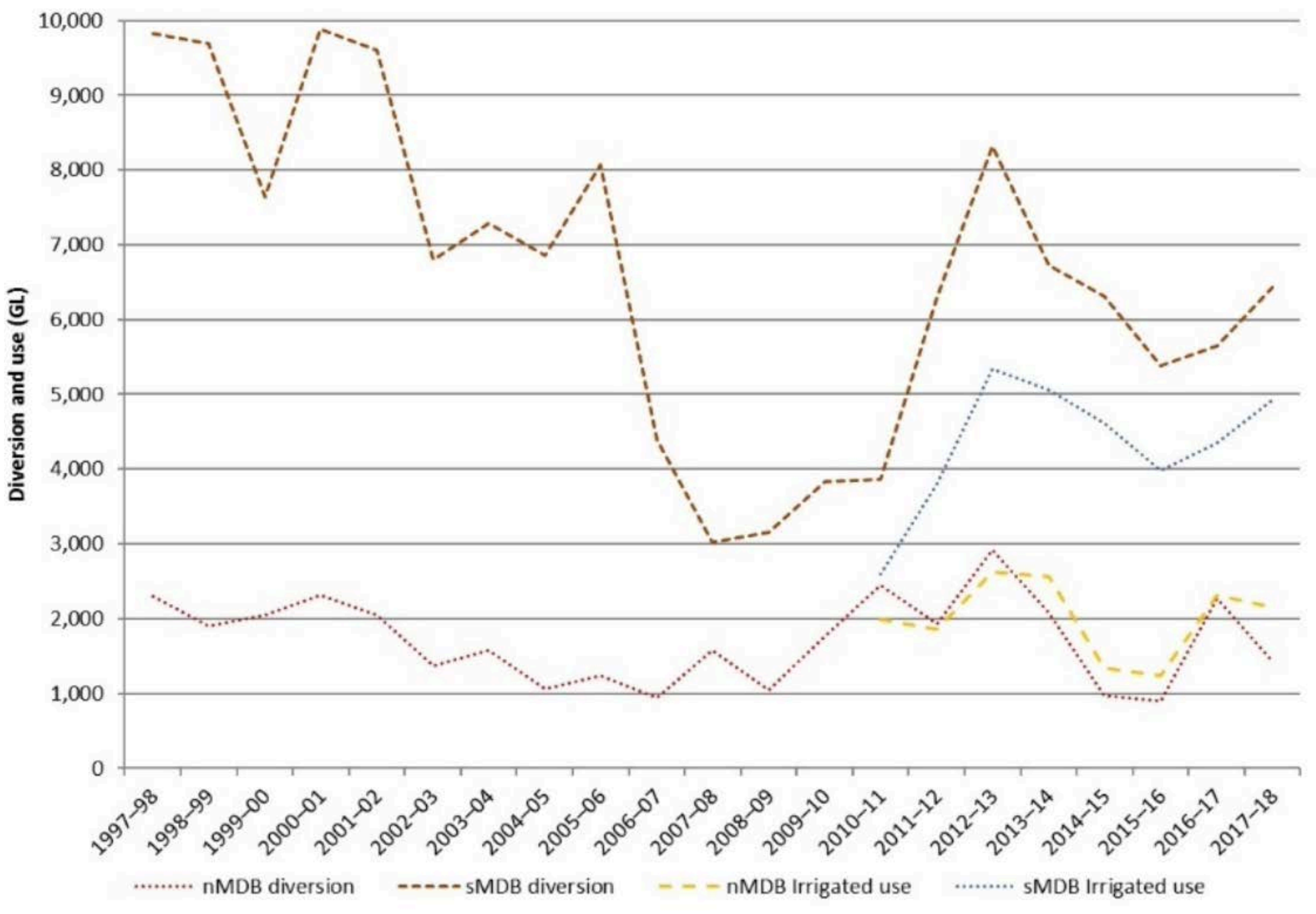


Figure 6-2 *Annual Diversions and Water use on Farm (Source: Authors' own based on MDBA 2019b and ABS 2018)*

good (MDBC, 1999). However, groundwater in the SMDB can be highly saline (Smitt *et al.*, 2002) making it less attractive for irrigated agriculture. To deal with SMDB salinity, and the salinity mobilized from overirrigation, Salinity Interception Schemes (SIS) have been developed to extract highly saline water before it enters the river system (Telfer *et al.*, 2012), but such systems are not needed in the NMDB. For this analysis we therefore assume that groundwater resources are of suitable quality in the NMDB to produce any agricultural commodity. This is important, as we are interested here in the transformation of irrigated agriculture production and management choices as a consequence of being able to access reliable resources in the face of future supply uncertainty (i.e., where extensive water storage and other infrastructure is not available).

2.3. Groundwater Use and the Murray-Darling Basin Plan

Groundwater use in the MDB is conservative compared to both the old baseline current diversion limit (CDL) and the new sustainable diversion limit (SDL) (see Figure 6-4). While groundwater use has been increasing since 2012-13 to 2017-18 due to increasing drought conditions, it is still far less than can theoretically be extracted (i.e., the SDL level as indicated). However, the value of groundwater for all users will increase during drought, and dependency on groundwater reserves in the MDB is expected to increase as the severity and frequency of droughts increase under future change climate (MDBA, 2019a).

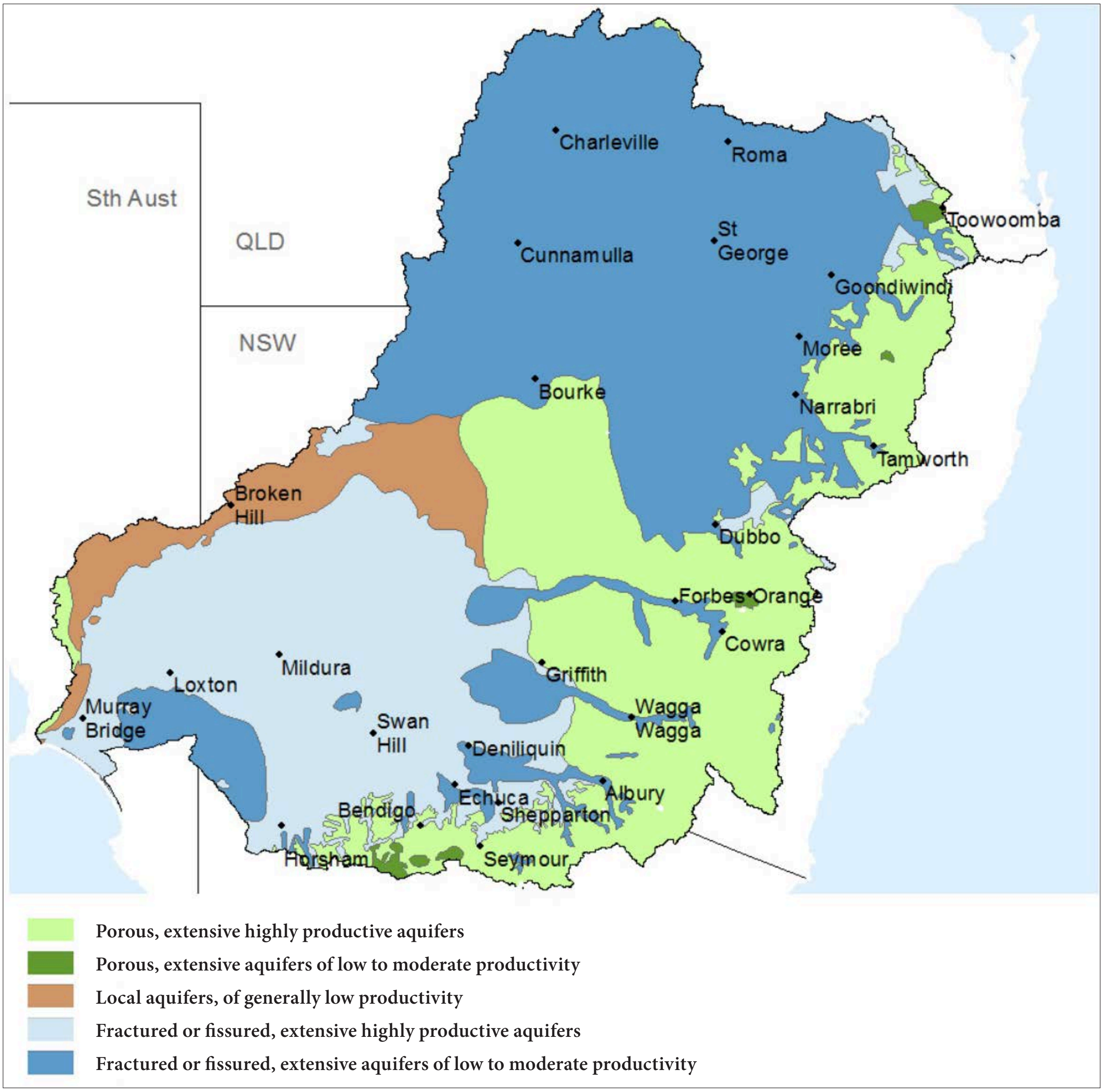


Figure 6-3 Groundwater Resources (Source: Author's own GIS mapping)

However, ultimately groundwater extraction may remain lower than the SDL for two reasons. First it may cost more to access groundwater than surface water depending on the conditions in place. Second the water resource plans that need to be developed by state governments to bring the new SDL extractions into law may be incomplete (MDBA, 2019a). As of December 2020 many of the 19 state-based plans for groundwater use submitted to the Murray–Darling Basin Authority (MDBA) who manage the Basin as an entity were still under review (MDBA, 2020b). This is a complex process. MDBA reports (2019a, 2020b) detail the complexity involved which includes how water is to be used to provide economic, cultural, social and environmental gains; the connectivity between surface and groundwater resources; the integrity of the aquifer and its hydrological relationships; and the risk posed to the groundwater system from over extraction. State governments have subsequently been monitoring and evaluating these resources to ensure that any new extractions do not pose a long-term risk to the system. Many users may be waiting for greater certainty before committing significant capital to groundwater extraction and use.

However, we anticipate that, once resources can be accessed, groundwater consumption will increase as the future becomes drier and hotter. In anticipation of this increased resource use, scientific debate has centered around alternative methodologies for quantifying and monitoring available groundwater resources (e.g. Chen *et al.*, 2016a; Chen *et al.* 2016b). Other work has focused on the current and future reliability of the resource (Schumacher *et al.*, 2018), the quality of the resource (Hart *et al.*, 2020), the connectivity of groundwater resources (Lamontagne *et al.*, 2014); and the role of groundwater in conjunctive water management (Ticehurst & Curtis, 2019). However, little to no economic analysis has been conducted on how access to more groundwater under a changing climate will change the value of that resource over time. The few examples which do exist include an MDBA commissioned work on the groundwater SDL which failed to quantify the economic benefits from higher access to groundwater (Deloitte Access Economics, 2015), and another study which only assessed the value of current groundwater in markets for a single catchment (de Bonviller *et al.*, 2020). Our chapter aims to address this deficiency in the literature.

Figure 6-4 *Groundwater Use in the MDB (Source: MDBA, 2019b)*

2.4. Summary

Surface water supply in the MDB is highly variable, and in the absence of storage systems to help mitigate that variability in the NMDB, increased access to reliable sources of groundwater has the capacity to positively transform agricultural production and management systems in economic and social terms—and environmentally if groundwater is used to achieve ecological objectives (e.g., wetland inundation). As climate change is anticipated to increase the severity and longevity of droughts, we seek to explore the value groundwater may have for agricultural producers. To understand how the value of highly reliable groundwater changes in response to droughts and floods we also need to deal with risk and uncertainty. For that we turn to the state-contingent approach, as discussed in the next section.

“The economic value of groundwater is not constant, we have to understand how the price elasticity of water is altered by the state of nature and alternative production systems such as annual and perennial crops”

03

Valuing Groundwater Resources under Uncertainty

3.1. Risk, Uncertainty and the Value of Water

Economics has two major approaches for dealing with uncertainty. The first approach, which is the dominant approach, utilizes mean and variance (e.g., stochastic functions) to explore inherent variability in systems. The second approach divides uncertainty into mutually exclusive alternative states of nature (e.g., drought, flood, normal) to represent the inherent variability in systems and to then explore how individuals respond to those states of nature. This is known as the State-Contingent Approach (SCA).

This difference is important as the first approach models a passive decision maker. In that case, once the event occurs, a decision maker continues on as before, failing to reallocate resources in response. This is akin to standing on a railway line and not stepping off the line when a train is approaching. Despite constant discussion about the limitations of this approach (Just & Pope, 1979; Rothschild & Stiglitz, 1971) it persists in the literature.

By contrast, a key feature of SCA is that it separates the uncertainty signal (i.e., in this case water supply uncertainty) from the producers’ response to that realized uncertainty (Chambers & Quiggin, 2000) so that both may be examined. This distinction is important because the economic value of groundwater is not constant (de Bonviller *et al*., 2020; MDBA, 2019a). Consequently, we have to understand how the price elasticity of water is altered by the state of nature and alternative production systems such as annual and perennial crops (Adamson *et al.*, 2017; Loch *et al.*, 2020a). A key driving force behind the value of water is the role it plays in each production system, and SCA helps us to explain this. Perennial production systems must always apply water in every state of nature to protect their capital base. The failure to irrigate can lead to crop death and expose the irrigators’ investment to unacceptable levels of risk. Consequently, perennial producers have a strong incentive to outbid annual producers in water markets—particularly if supply is short. This threat to long run capital investments and the options available to producers is provided in more detail by Adamson and Loch (Accepted 26 May 2020).

While the above work helps illustrate perennial agricultural producer behavior and simulate any outcomes in response, it does not optimize total resource use within a basin. To do that, we expand an SCA model for the MDB originally developed by Adamson *et al.* (2007). This forms the basis of our analysis.

3.2. An Overview of the Optimization Model

Reallocating water within a closed basin like the MDB is a complex issue. We have to understand the drivers of change (water supply, social, economic, environmental), the policy instruments and incentives that are used to drive the transformation, and how risk and uncertainty alter the drivers and behavioral responses to that uncertainty signal (Gómez Gómez *et al.*, 2018).

Building on past work (e.g. Adamson *et al.*, 2007; Adamson *et al.*, 2009; Quiggin *et al.*, 2010), Adamson (2015) transformed the SCA MDB optimization model into one that explored net welfare changes from implementation of the MDB Plan. Detailed methodological notes, all data sets and assumptions underpinning the model can be found in Adamson (2015). The following material summarizes the model and the adaption required for this analysis

3.2.1. Introduction to the Model

The model was built to explore what value SCA (Chambers & Quiggin, 2000) has in allocating water resources under uncertainty. The model was subsequently used to provide input into The Garnaut Climate Change Review which was a critical report for Australia that examined the impacts of climate change on the Australian economy, the costs of adaptation and mitigation, and the international context in which climate change is experienced and negotiated (Quiggin *et al.*, 2008), the MDB Plan (Adamson *et al.*, 2011; Mallawaarachchi *et al.*, 2010), and a number of journal chapters already listed.

In simple terms, the model utilizes the conjunctive water resource data presented in Section 2.1 to characterize water supply arrangements in a normal year. Based on this, a drought year will only provide 60% of that normal supply while wet years will supply 120%. The frequency of those states of nature (i.e., normal, drought and wet) have a probability of 50%, 20% and 30% respectively.

“We have to understand the drivers of change, the policy instruments and incentives that are used to drive the transformation, and how risk and uncertainty alter the drivers and behavioral responses to that uncertainty signal”

So defined, the model then utilizes a constrained optimization approach to allocate water at a catchment scale to maximize economic return from irrigation. It utilizes a directed flow structure (19 agricultural catchments, mandated demand from the City of Adelaide, and environmental flow requirements at the rivers’ terminal node in the Coorong), salinity targets to replicate water quality, bio-physical reality and institutional setting constraints to replicate policy incentives. The model then helps understand the opportunity cost (economic return and changes to water quality) of using water across space (i.e., catchments) and time (three states of nature: dry, wet and normal, that occur with a given frequency).

The model is set up with a single individual as decision-maker with the capacity to play a game against nature by allocating irrigation resources across the 19 catchments to produce alternative commodities. As such it is forward looking and determines the optimal choice of production systems to maximize income. Finally, specific input and output sets for all states of nature highlight the production system requirements and outputs they generate. This way producer behavior can be modelled to reallocate resources between alternative SCA described production systems.

3.2.2. SCA Production Systems

Critical to the model is the representation of alternative production systems. Here care is needed to model how producers allocate inputs (land, water, variable costs, fixed costs and labor) between production choices by state of nature (i.e., normal, drought, wet year). Care is needed to reflect reality. If a producer engages in the choice to produce perennials, then that perennial crop must be present in all states of nature. Alternatively, an annual producer may choose to irrigate every year and/or be opportunistic in irrigation and only irrigate in one or two states of nature (i.e., normal and wet), while defaulting to a dryland or fallow crop in dry states of nature. This approach helps represent how decision makers alter their production systems in response to uncertainty where they can.

Critical to any analysis is the inclusion of all inputs listed in Table 6-1 above, which allows the model to deal with capital investments. Capital is treated as an annual fixed cost payment over a 20-year repayment period. This then allows for the economic return (i.e., farm income from alternative agricultural crop investments less total production costs) to be explored across all states of nature.

3.2.3. Water Use

Prior versions of the model allowed producers to grow production systems with either ground or surface water. However, to represent the net change in total water resources (decreased surface water and increased groundwater), the production systems were doubled so that output could come from either groundwater or surface water, but not both. While this may not be fully representative of realistic options, it provides clarity on the value of each water resource. To facilitate this analysis, a new set of inputs and outputs was also required to reflect changes in production costs. Note that for ease of analysis, the cost to purchase any new groundwater releases was not included.

The separation of water into ground and surface resources allowed two major advances. First the model can now explore the reliability of those rights by catchment, across time. For this analysis we assume all new water is always available due to the institutional rigor that is being applied in state water resource plans (as described above) to ensure that access is possible. Second the model can represent the change in the SDL from any existing entitlements (see Table 6-1). Our ability to utilize the directed flow network and trading rules listed in Table 6-1 allowed the SDL to be obtained at least cost to production. This then incorporates the institutional objectives of the MDB Plan.

3.2.4. Incorporating Climate Change into the Model

Perhaps one of the greatest contributions to water economics by this model was achieved in Adamson *et al*. (2009). Here, the capacity for SCA to describe what happens by state of nature (to water supply), and the frequency with which each state occurs, allows climate change to be more accurately represented and modeled. Consequently, the way water supply changes can be described for each state of nature (e.g., more severe droughts) and the frequency with which each state occurs (e.g., increased drought events). This description allows for an exploration of the impacts i) that changes in water supply have by a mean reduction in water supply (i.e., proportional change of agricultural production in each state), ii) when water supply by states do not change but the frequency of each state does, or iii) from a combination of both. Thus, we can predict that a new and reliable source of groundwater will increase production choices and be more valuable in the future.

The combination of a water flow network (i.e., a representation of the river system), biophysical limits (i.e., water volumes, salinity and choke points that constrain delivery) and institutional objectives (i.e., flow targets to the Coorong), then help restrict water use under a changing climate, even if the existing reliability of rights are not altered—where alteration of water right reliability is not possible within the Australian system.

Our analysis thus explores climate change in two ways. First the expected change in water supply out to 2050 and 2100 have been explored based on new climate change scenarios where CO_2 emissions stabilize at 450 parts-per-million (ppm) (Quiggin *et al*., 2008). The model produces results for combinations of atmospheric CO_2 concentrations and year, such as 450 ppm and 2050, and this data has been used to align with other studies (e.g., the Garnaut Review). The reduction in normal state surface water supply is assumed to be 10% and 20% for the year 2050 and 2100 respectively. Assumed supply under drought (i.e., 60% of normal) and wet states (i.e., 120% of normal) remain constant. These scenarios are described as “450 ppm, year 2050” and “450 ppm, year 2100”.

To model increasing drought states we change the probability of each of the states of nature occurring, where the new climate occurs with the following frequencies: normal (50%), drought (30%), and wet state (20%). Under these new state outcomes we leave the water supply descriptions as per the base model (i.e., the CDL scenario) and label this scenario as Drought states where it reports economic returns across all three states.

Ultimately, for all scenarios we assume that groundwater access does not reduce. As per the discussion above, the groundwater SDL should not have increased, since decisions to allow increased access were made in light of climate change expectations.

3.3. Summary

This has been a brief description of the model used and highlights the major changes that occurred to model the current and future value of groundwater. While Adamson (2015) includes a wider discussion on what happens to surface rights, this version extends the findings on the value of groundwater. The next section outlines the results of our analysis.

04

Welfare Changes from Increased Groundwater

4.1. Moving to the Sustainable Diversion Limits

In the model outputs the first noticeable thing is that, under the transition from the CDL to the new SDL, economic return (welfare) increases, while the total consumption of water reduces. Economic return in the model is the net return from producing an agricultural crop (e.g., cotton). However, while total water (surface and groundwater) use has reduced, augmented access to reliable groundwater transforms agricultural production and management systems to increase economic returns (Table 6-3). For the CDL, a total of 15,049 GL of surface and groundwater resources produced a total of $3 billion of economic returns in the NMDB ($241 million from groundwater use and $967 million from surface water) and

Table 6-3 Economic Return (Welfare) Changes from the MDB Plan, by scenario

		NMDB		SMDB		TOTAL
		GW	SW	GW	SW	
Welfare ($'m)	CDL	$241.3	$967.3	$399.3	$1,473.9	**$3,081.8**
	SDL	$340.2	$957.4	$636.3	$1,360.3	**$3,294.2**
	450ppm, year 2050	$390.4	$762.8	$645.6	$1,338.3	**$3,137.1**
	450ppm, year 2100	$413.4	$728.7	$645.6	$1,337.5	**$3,125.2**
	Drought States	$406.1	$820.2	$582.3	$1,020.8	$2,829.5
Water Used (ML)	CDL	1,149.4	3,899.1	1,223.3	8,777.0	15,048.7
	SDL	1,789.8	3,709.9	1,512.0	6,478.3	13,490.1
	450, 2050	1,789.9	3,083.4	1,512.0	6,480.5	12,865.8
	450, 2100	1,789.9	3,044.7	1,512.0	6,480.5	12,827.1
	Drought States	1,789.9	3,563.8	1,512.0	6,488.0	13,353.7

Table 6-4 Area irrigated (1,000 Ha)

	NMDB		SMDB		TOTAL
	GW	SW	GW	SW	
CDL	254	1,151	221	1,079	**2,705**
SDL	408	1,100	247	817	**2,571**
450, 2050	477	845	243	760	**2,326**
450, 2100	481	829	243	761	**2,313**
Drought States	377	1,052	234	555	**2,218**

SMDB ($399 million from groundwater use and $1,474 million from surface water use). By contrast, under the SDL a total of 13,490GL of water use produces $3.3 billion in economic returns following the transformation. This arises from new NMDB ($340 million from groundwater, and $957 million from surface water) and SMDB production and management systems ($636 million from groundwater and $1,360 million from surface water).

The change in land use by scenario is presented in Table 6-4 and Figure 6-5. We can see from Figure 6-5 that access to extra groundwater allows for an increase of over 150,000 hectares (Ha) of land (CDL versus SDL) in the NMDB. While there is a slight increase in perennial area, most land is utilized to produce cotton and grains. At the same time, we see an increase in the SMDB area irrigated by groundwater (6,000 Ha). The reason why economic returns are so great in the SMDB as a consequence of increased groundwater use (i.e., $636 million under the SDL versus $399 million under the CDL) is that there is a reallocation of land towards higher-valued perennials (increase of over 40,000 Ha) from the increased access to reliable water.

A frequent observation for Australia is that land is not a binding constraint; only water. In the NMDB, the development of an additional 150,000 Ha of land irrigated in all states (i.e., perennial cropping supported by groundwater resources) will create second round benefits that may help negate the drought shocks that occur in regional communities—although at the expense of increased capital exposure risk in the face of uncertain future climate outcomes. Logically as access to surface water reduces, the dairy industry is the biggest looser with over 200,000 Ha of land removed. However, the recent Millennium drought highlighted the ability for dairy producers to adapt a SCA production mentality as they were able sell water and purchase fodder to continue production (Mallawaarachchi *et al.*, 2017).

"The recent Millennium drought highlighted the ability for dairy producers to adapt a SCA production mentality as they were able sell water and purchase fodder to continue production"

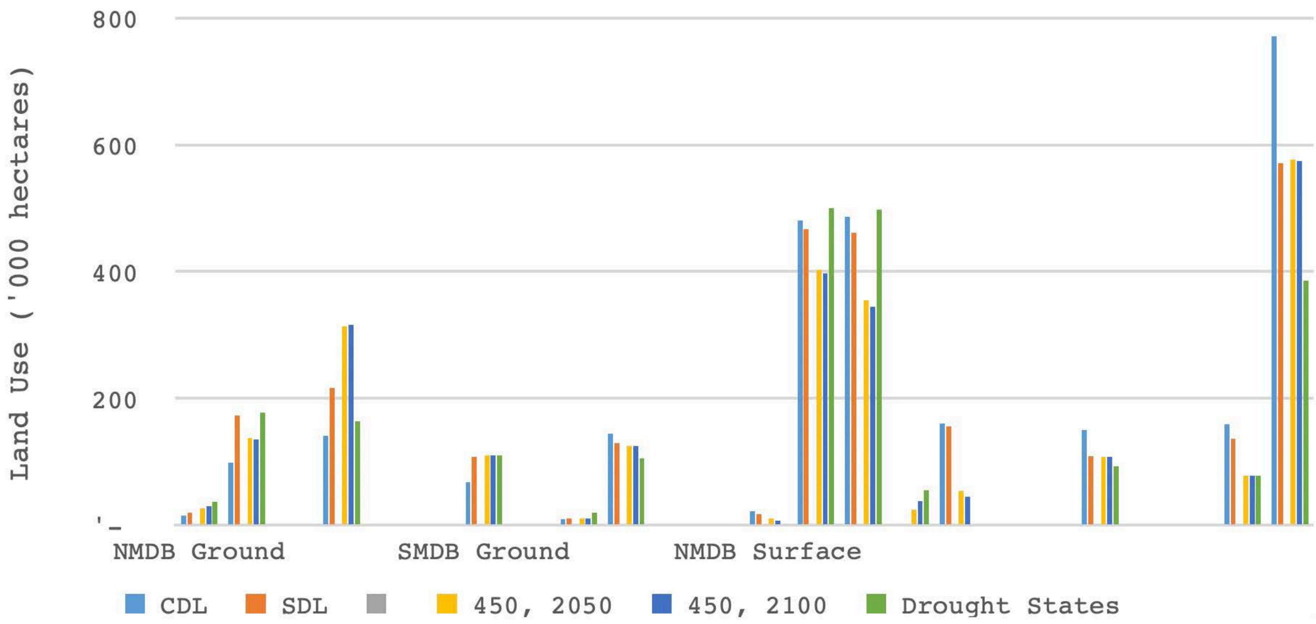


Figure 6-5 *Land Use Production Systems by Scenario, Location and Water Source*

4.2. Climate Change Impacts on Welfare

The two climate change impacts: 450;2050 and 450;2100 and increased drought states highlight the benefits of highly reliable groundwater under a changing climate. The economic return from groundwater continues to increase as water becomes scarcer (Table 6-5). For both 450 ppm scenarios, extra groundwater offsets reductions in surface water despite a total reduction in water supply between 10% and 20%. However, if droughts become more frequent, the extra groundwater may not offset the total loss of surface water via a changing climate.

We can see the impact that increased droughts have on production in Figure 6-5 where in the NDMB all surface water basically is used to grow cotton (i.e., in normal and wet years only) and Opportunistic Cotton (Opp Cotton) that is only grown in wet years. Again, the dairy industry loses approximately another 200,000 Ha of production seriously threatening its future viability. While this may be seen as unrealistic in countries where government intervention is the norm, Australian farmers are largely left to make their own investment decisions as food security is not a concern.

The converse is true for surface water where a reduction in total supply reallocates water towards high returns (e.g., in the SMDB away from dairy). However, the influence of climate change is reflected by increased economic returns per ML for groundwater. This is most notable in the SMDB where economic returns increase by over 30% from increased groundwater access (CDL versus the 450 scenarios). Under these access improvements, groundwater becomes akin to gold; that is, compared to highly variable surface water rights, groundwater provides more certainty and economic value. Finally, while not as evident in the SMDB, the economic returns from surface water decrease. Any reduction in economic returns from surface water in the NMDB is likely due to the absence of large capital infrastructure to help mitigate supply variability.

Therefore, as the economic returns from water use diverge between surface water and groundwater, the implementation of the MDB Plan will create wealth for owners—or gifted recipients—of groundwater property rights. As these new groundwater rights become available it will be interesting to see how they transition into private hands as a result of that increased value.

4.3. Value of Groundwater Under a Changing Climate

The economic return from the alternative water sources is also shown in Table 6-5. Here we see basic economics working; that is, how scarcity and reliability alter economic return. Initially the increased supply of groundwater devalues the return that can be made by access to increased groundwater and transformations under the shift from CDL to SDL in the NMDB. In the SMDB, increased groundwater allows new greenfield sites to emerge and for the production of more annual crops. As the SMDB already has extensive investments in support infrastructure (e.g., packing sheds, transportation hubs, proximity to markets, labour supplies etc.) an increase in perennial production systems is both logical and straightforward.

4.4. Summary

The MDB Plan has the capacity to create wealth by increasing the overall reliability of total conjunctive water supplies. However, the gains are not uniform by catchment nor between the SMDB and the NMDB. This wealth gain may offset come losses associated with climate change (admittedly the scenario here is very optimistic as it now appears that the world hopes to stop at around 550 ppm). And as the reliability of surface water deteriorates, surface water rights will continue to be worth less and less, but highly reliable rights (surface or groundwater) will appreciate.

Table 6-5 Economic Return by Water Supply ($/ML)

	NMDB		SMDB	
	GW	SW	GW	SW
CDL	$210	$222	$326	$168
SDL	$190	$244	$421	$225
450, 2050	$218	$194	$427	$222
450, 2100	$231	$186	$427	$222
Drought States	$227	$209	$385	$222

05

Concluding Comments

While water infrastructure (dams, channels) is often promoted as a prime mechanism for drought-proofing a nation, the reality is we cannot make it rain and existing/new water infrastructure may prove to be in the wrong place if rainfall patterns alter under climate change. Additionally, there are very few places left in the MDB that are suitable for developing new dams (Loch *et al.*, 2020b).

Groundwater aquifers thus provide several advantages for future water resource and irrigation opportunities to help offset the effects of climate change. First, these resources require minimal costs to develop when compared to large scale dams and distribution networks. Second, they allow greater opportunities for greenfield sites that are not constrained by the existing engineering infrastructure yet to be developed.

However, this natural capital (aquifer system) must be maintained and preserved via sustainable use. As discussed in Section 2.3, current scientific evidence suggests the groundwater SDL will in fact be sustainable. As climate change realities set in, access to a highly reliable and sustainable source of groundwater will provide golden (consistent income) returns for its owners and those who by association provide production inputs. Therefore, we expect significant future pressure to increase groundwater extractions. If this occurs, we may simply be creating another legacy for future generations to deal with where we degrade the natural capital (i.e., the storage system, the volume stored and its quality).

> *"Any new groundwater resources will need a process of careful allocation, constant monitoring and periodic evaluation for sustainability"*

Therefore, perhaps the best way forward is to adopt a precautionary approach where the amount utilized is less than what is suggested as sustainable until the future has been revealed. To be truly sustainable, understanding the risk to future supply, the risks to the reliability of water percolation back into groundwater, and the risks to aquifer integrity from over consumption must be understood. This may involve regulatory restrictions on the development of new perennial production sites, but in our view that is unlikely in the current political climate. Further, while increased access to groundwater provides the capacity for the development of an expanded perennial industry, other considerations such as access to transport, markets, labor and the large-scale capital investment (packing sheds, refrigeration equipment, etc.) may be equally important as the access to water. This is especially true for Australia where food security is not a priority, and approximately 70% of agricultural product is exported to close neighbors (e.g., SE Asian countries).

As we have shown, in the short run, access to reliable groundwater may make it more likely that irrigators will transition to perennial commodities in the NMDB; particularly if export returns are high as explained above. Profitable commodities (e.g., almonds) will require capital systems to change—which in turn may increase both community viability and capital risk. Only time will tell. In the SMDB where the associated capital already exists, agricultural producers are far more likely to also transition toward greenfield perennial systems under any capacity to access and utilize secure reliable groundwater.

Regardless of the industry that develops (including non-agricultural sectors such as mining) access to more highly reliable groundwater provides economic growth for a region in all states of nature. To maximize net social welfare, including capacity to address positive externalities for environmental right holders who can have improved access to (previously) constrained rights, reallocation should occur through the existing market infrastructure—that admittedly is unique to Australia. Australia has a highly developed water market system that has the capacity to achieve such resource reallocation objectives. (de Bonviller *et al.*, 2020; Gómez Gómez *et al.*, 2018). The rights should also be sold off slowly, over time, to maximize the income from sales and our capacity to halt sales if new information concerning their reliability is revealed. This may help negate the current impact of droughts where shocks to agricultural income place a break on regional economic activity (PC, 2009). It must also be said that it is equally possible that, depending on the structure of rights held by an individual irrigator, groundwater resources may not be utilized due to cost differences in using surface water.

As stated above, government reports on groundwater resources, SDL constraints and utilisation are still largely being finalized and delivered. As such, this analysis is a timely exploration of the economic value of groundwater. However, our analysis does not explore the future reliability of groundwater with respect to recharge rates, depletion, and/or aquifer stability—that is the domain of scientific investigations. Whatever happens, any new groundwater resources will need a process of careful allocation, constant monitoring and periodic evaluation for sustainability.

References

ABS. (2018). Water Use on Australian Farms 2018-19: available at https://www.abs.gov.au/statistics/industry/agriculture/water-use-australian-farms.

Adamson, D. (2015). *Restoring the Balance: Water Reform & the Murray Darling Basin Plan*. PhD (Doctor of Philosophy), The University of Queensland, Brisbane, Australia. Retrieved from http://espace.library.uq.edu.au/view/UQ:348613/s3001062_finalthesis_phd.pdf.

Adamson, D. & Loch, A. (2018). Achieving environmental flows where buyback is constrained. *The Australian Journal of Agricultural & Resource Economics*, 62(1), pp. 83-102.

______. (Accepted 26 May 2020). Reducing the risk of water efficiency capital exposure to future scarcity shocks. *Land Economics*.

Adamson, D., Loch, A. & Schwabe, K. (2017). Adaptation responses to increasing drought frequency. *Australian Journal of Agricultural and Resource Economics*, 61(3), pp. 385-403. DOI: 10.1111/1467-8489.12214.

Adamson, D., Mallawaarachchi, T. & Quiggin, J. (2007). Water use and salinity in the Murray Darling Basin: A state-contingent model. *Australian Journal of Agricultural and Resource Economics*, 51(3), pp. 263-281.

______. (2009). Declining inflows and more frequent droughts in the Murray–Darling Basin: climate change, impacts and adaptation. *Australian Journal of Agricultural and Resource Economics*, 53(3), pp. 345-366. DOI: 10.1111/j.1467-8489.2009.00451.x.

Adamson, D., Quiggin, J. & Quiggin, D. (2011). *Water Supply Variability & Sustainable Diversions Limits: Issues to Consider in Developing the Murray-Darling Basin Plan* Brisbane. Retrieved from https://www.mdba.gov.au/sites/default/files/archived/basinplan/1717-WaterSupplyVariability&SustainableDiversionLimitsIssuesToConsider.pdf.

Brunke, M. & Gonser, T. O. M. (1997). The ecological significance of exchange processes between rivers and groundwater. *Freshwater Biology*, 37(1), pp. 1-33. DOI: 10.1046/j.1365-2427.1997.00143.x.

Bureau of Meteorology. (2011). *National Water Account 2010*. Canberra: Bureau of Meteorology, Canberra. Retrieved from http://www.bom.gov.au/water/nwa/2010.

Chambers, R. G. & Quiggin, J. (2000). *Uncertainty, production, choice, and agency: The state-contingent approach*. New York: Cambridge University Press.

Chen, J. L., Famigliett, J. S., Scanlon, B. R. & Rodell, M. (2016a). Groundwater Storage Changes: Present Status from GRACE Observations. *Surveys in Geophysics, 37*(2), pp. 397-417. DOI: 10.1007/s10712-015-9332-4.

Chen, J. L., Wilson, C. R., Tapley, B. D., Scanlon, B. R. & Güntner, A. (2016b). Long-term groundwater storage change in Victoria, Australia from satellite gravity and in situ observations. *Global and Planetary Change, 139*, pp. 56-65. DOI: https://doi.org/10.1016/j.gloplacha.2016.01.002.

Chiew, F. H. S., Teng, J., Kirono, D., Frost, A., Bathols, J., Vaze, J., Viney, N. R., Young, W. J., Hennessy, K. J. & Cai, W. (2008). *Climate data for hydrologic scenario modelling across the Murray-Darling Basin: A report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project* Australia.

Commonwealth of Australia. (2008). *Water Act 2007* Canberra: Office of Legislative Drafting and Publishing, Canberra.

Crosbie, R. S., McCallum, J. L., Walker, G. R. & Chiew, F. H. S. (2008). *Diffuse groundwater recharge modelling across the Murray-Darling Basin* Australia. Retrieved from https://publications.csiro.au/rpr/download?pid=procite:714158ac-5682-41dc-878e-b3f6a052fad6&dsid=DS1.

de Bonviller, S., Wheeler, S. A. & Zuo, A. (2020). The dynamics of groundwater markets: Price leadership and groundwater demand elasticity in the Murrumbidgee, Australia. *Agricultural Water Management, 239*, 106204. DOI: https://doi.org/10.1016/j.agwat.2020.106204.

Deloitte Access Economics. (2015). *Socio-economic impacts of Groundwater Amendments to the Basin Plan: Report Commissioned by the Murray-Darling Basin Authority* Canberr a, Australia. Retrieved from https://www.mdba.gov.au/sites/default/files/pubs/Groundwater-S%26E-impacts.pdf.

Gómez Gómez, C. M., Pérez-Blanco, C. D., Adamson, D. & Loch, A. (2018). Managing Water Scarcity at a River Basin Scale with Economic Instruments. *Water Economics and Policy, 04*(01), 1750004. DOI: 10.1142/S2382624X17500047.

Hart, B., Walker, G., Katupitiya, A. & Doolan, J. (2020). Salinity Management in the Murray–Darling Basin, Australia. *Water, 12*, 1829. DOI: 10.3390/w12061829.

Heberger, M. (2011). Australia's Millennium Drought: Impacts and Responses. In P. Gleick (ed.), *The World's Water*, pp. 97-125. Island Press/Center for Resource Economics.

Just, R. E. & Pope, R. D. (1979). Production function estimation and related risk considerations. *American Journal of Agricultural Economics, 61*(2), pp. 276-284. DOI: 10.2307/1239732.

Kirby, M., Bark, R., Connor, J., Qureshi, M. E. & Keyworth, S. (2014). Sustainable irrigation: How did irrigated agriculture in Australia's Murray–Darling Basin adapt in the Millennium Drought? *Agricultural Water Management, 145*, pp. 154-162. DOI: http://dx.doi.org/10.1016/j.agwat.2014.02.013.

Knapp, K. & Baerenklau, K. A. (2006). Ground Water Quantity and Quality Management: Agricultural Production and Aquifer Salinization over Long Time Scales. *Journal of Agricultural and Resource Economics, 31*(3), pp. 616-641.

Lamontagne, S., Taylor, A. R., Cook, P. G., Crosbie, R. S., Brownbill, R., Williams, R. M. & Brunner, P. (2014). Field assessment of surface water–groundwater connectivity in a semi-arid river basin (Murray–Darling, Australia). *Hydrological Processes, 28*(4), pp. 1561-1572. DOI: https://doi.org/10.1002/hyp.9691.

Loáiciga, H. A. (2003). Climate Change and Ground Water. *Annals of the Association of American Geographers, 93*(1), pp. 30-41. DOI: 10.2307/1515321.

Loch, A., Adamson, D. & Auricht, C. (2020a). (g)etting to the point: The problem with water risk and uncertainty. *Water Resources and Economics, 32*, 100154. DOI: https://doi.org/10.1016/j.wre.2019.100154.

Loch, A., Adamson, D. & Dumbrell, N. P. (2020b). The Fifth Stage in Water Management: Policy Lessons for Water Governance. *Water Resources Research, 56*(5), e2019WR026714. DOI: 10.1029/2019wr026714.

Love, G. (2005). Impacts of climate variability on regional Australia. In *ABARE Outlook Conference Proceedings (National Agricultural and Resources Outlook Conference Proceedings), Climate Session Papers*, pp. 10–19. Canberra: Australian Government Department of Agriculture, Fisheries and Forestry.

Mallawaarachchi, T., Adamson, D., Chambers, S. & Schrobback, P. (2010). *Economic Analysis of Diversion Options for the Murray-Darling Basin Plan: returns to irrigators under reduced water availability: A commissioned study for the Murray-Darling Basin Authority prepared by the University of Queensland* Brisbane: M.-D. B. Authority. Retrieved from http://www.mdba.gov.au/files/bp-kid/1391-Economic-analysis-diversion-options.pdf.

Mallawaarachchi, T., Auricht, C., Loch, A., Adamson, D. & Quiggin, J. (2020). Water allocation in Australia's Murray–Darling Basin: Managing change under heightened uncertainty. *Economic Analysis and Policy, 66*, pp. 345-369. DOI: https://doi.org/10.1016/j.eap.2020.01.001.

Mallawaarachchi, T., Nauges, C., Sanders, O. & Quiggin, J. (2017). State-contingent analysis of farmers' response to weather variability: irrigated dairy farming in the Murray Valley, Australia. *Australian Journal of Agricultural and Resource Economics, 61*(1), pp. 36-55. DOI: 10.1111/1467-8489.12193.

MDBA. (2012). *Water Act 2007: Basin Plan* Canberra, Australia. Retrieved from https://www.legislation.gov.au/Details/F2012L02240/3f0f4bcc-7985-4bd4-b5d1-79c6cc9fe145.

______. (2019a). *Statement of expectations for managing groundwater Groundwater management in the Murray–Darling Basin* Canberra, Australia. Retrieved from https://www.mdba.gov.au/sites/default/files/pubs/Statement-of-expectations-for-managing-groundwater-in-the-MDB.pdf.

______. (2019b). *Transition Period Water Take Report 2017–18 : Report on Cap compliance and transitional SDL accounting* Canberra, Australia. Retrieved from https://www.mdba.gov.au/sites/default/files/pubs/transition-period-water-take-report-2017-18_0.pdf.

______. (2020a). *Murray-Darling Basin water in government storages: 30 September 2020* Canberra, Australia. Retrieved from https://www.mdba.gov.au/sites/default/files/water-in-storages/weeklybasinreports/Basin-Storage-20200930.pdf.

______. (2020b). *Water resource plans – September 2020 quarterly report* Canberra, Australia. Retrieved from https://www.mdba.gov.au/sites/default/files/pubs/water-resource-plan-quarterly-report-august-2020.pdf.

MDBC. (1999). *Murray-Darling Basin Groundwater - a Resource for the Future* Canberra, Australia. Retrieved from https://www.mdba.gov.au/sites/default/files/archived/mdbc-GW-reports/2173_GW_a_resource_for_the_future.pdf.

Murray-Darling Basin Commission. (2006). Murray-Darling Basin Water Resources Fact Sheet. *Murray Darling Basin Commisson, July 2006*. Retrieved from http://www2.mdbc.gov.au/__data/page/20/MDB-WaterResources-FactSheet-July2006.pdf.

PC. (2009). *Government Drought Support* Melbourne, Australia. Retrieved from https://www.pc.gov.au/inquiries/completed/drought/pdf/drought-support-draft.pdf.

Quiggin, J., Adamson, D., Chambers, S. & Schrobback, P. (2010). Climate change, uncertainty, and adaptation: The case of irrigated agriculture in the Murray–Darling Basin in Australia. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie, 58*(4), pp. 531-554. DOI: 10.1111/j.1744-7976.2010.01200.x.

Quiggin, J., Adamson, D., Schrobback, P. & Chambers, S. (2008). *Garnaut Climate Change Review: The Implications for Irrigation in the Murray-Darling Basin* RSMG, School of Economics, The University of Queensland. Retrieved from https://www.researchgate.net/publication/43521183_Garnaut_climate_change_review_The_implications_for_irrigation_in_the_Murray-Darling_Basin.

Rothschild, M. & Stiglitz, J. E. (1971). Increasing risk II: Its economic consequences. *Journal of Economic Theory, 3*(1), pp. 66-84. DOI: http://dx.doi.org/10.1016/0022-0531(71)90034-2.

Scanlon, B. R., Faunt, C. C., Longuevergne, L., Reedy, R. C., Alley, W. M., McGuire, V. L. & McMahon, P. B. (2012). Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proceedings of the National Academy of Sciences, 109*(24), pp. 9320-9325. DOI: 10.1073/pnas.1200311109.

Schumacher, M., Forootan, E., van Dijk, A. I. J. M., Müller Schmied, H., Crosbie, R. S., Kusche, J. & Döll, P. (2018). Improving drought simulations within the Murray-Darling Basin by combined calibration/assimilation of GRACE data into the WaterGAP Global Hydrology Model. *Remote Sensing of Environment, 204*, pp. 212-228. DOI: https://doi.org/10.1016/j.rse.2017.10.029.

Smerdon, B. D., Ransley, T. R., Radke, B. M. & Kellett, J. R. (2012). *Water resource assessment for the Great Artesian Basin: A report to the Australian Government from the CSIRO Great Artesian Basin Water Resource Assessment* Canberra, Australia. Retrieved from https://publications.csiro.au/rpr/download?pid=csiro:EP132686&dsid=DS5.

Smitt, C., Jolly, I., Dowling, T. & Walker, G. (2002). *Assessment of Historic Data for the Murray-Darling Basin Ministerial Council's End-of-Valley Target Stations* Canberra, Australia: CSIRO. Retrieved from http://www.clw.csiro.au/publications/technical2002/tr40-02_part1.pdf.

Telfer, A., Burnell, R. & Charles, A. (2012). Salt Interception Schemes and instream processes In Jaensch D. & Cooke J. (eds.) *Mallee Salinity Workshop, May 30 2012*.

Ticehurst, J. L. & Curtis, A. L. (2019). Assessing Conjunctive Use Opportunities with Stakeholders in the Murray-Darling Basin, Australia. *Journal of Water Resources Planning and Management, 145*(5), 05019008. DOI:10.1061/(ASCE)WR.1943-5452.0001069.

Young, M. & McColl, J. (2009). Double trouble: the importance of accounting for and defining water entitlements consistent with hydrological realities. *Australian Journal of Agricultural and Resource Economics, 53*, pp. 19-35. DOI: 10.1111/j.1467-8489.2007.00422.x.

7

Drivers of Groundwater Salinity and Potential for Freshwater Abstraction on a Semi-Arid Coral-limestone Island in Sri Lanka

Simon G. Craig, Chen Lester R. Wu, Tibor Y. Stigter and Jacobus Groen

Simon G. Craig, IHE Delft – Institute of Water Education, Delft, The Netherlands.
e-mail: simongcraig@gmail.com
Chen Lester R. Wu, IHE Delft – Institute for Water Education, Delft, The Netherlands.
e-mail: crwu2@up.edu.ph
Tibor Y. Stigter, IHE Delft – Institute for Water Education, Delft, The Netherlands.
e-mail: t.stigter@un-ihe.org
Jacobs Groen, Groen Water Solutions, The Netherlands.
e-mail: groen.watersolutions@gmail.com

Abstract

This study assesses the spatial distribution and hydrochemistry of fresh and saline groundwater and the impacts of abstraction on a small coral-limestone island – Delft Island, Sri Lanka, within a semi-arid setting. Similar to other coral-limestone islands, the groundwater in the study area occurs as a lens of freshwater overlying seawater in a highly permeable aquifer. Short-term growth in population and tourism, combined with shoreline retreat due to sea-level rise, is expected to affect the availability of groundwater on the island, and the current study further looks at solutions towards sustainable groundwater abstraction practices for improved groundwater management. Field assessments, involving well inventories, sampling for stable water isotopes and hydrochemistry, interviews with residents, and one-dimensional (1D) vertical electrical soundings (VES), were combined with steady-state analytical solutions and numerical modelling using MODFLOW & MT3DMS, to evaluate the spatial distribution of fresh and saline water, its sensitivity to recharge, and the impacts of abstraction. Results reveal a thin and irregularly shaped freshwater lens (FWL) overlying seawater with a relatively thin transition zone, as well as small-scale heterogeneity in the aquifer and localised upconing below some pumping wells. Estimated recharge is high, in particular in the elevated (3-6 m +msl) parts of the island covered by sand deposits. Findings from stable water isotope analyses suggest the meteoric origin (i.e. originating from precipitation) of surface water and groundwater, with salinization mainly caused by mixing with seawater and evaporation. The very shallow occurrence of seawater is mostly a result of high aquifer transmissivity, low elevation and low hydraulic heads, as well as the presence of lagoons in the centre of the island that are inferred to be in hydraulic connectivity with the ocean. High alkalinities and CO_2 pressures in saline groundwater near the coast further suggest the possible role of infiltration of saline water from overwash and subsequent percolation through the soil zone. Elevated nitrate concentrations in both groundwater and surface water in some areas reveal anthropogenic contamination from sewage and agricultural runoff. Steady-state simulations highlight that the FWL and transition zone thickness are highly sensitive to recharge and mechanical dispersion. Solutions towards increasing groundwater availability for abstraction, therefore, include managed recharge in the sandy aquifer during the rainy season and recovery through horizontal abstraction techniques. These techniques are currently being studied in more detail, which should ultimately result in a pilot employing these techniques on the island.

Keywords

Freshwater lens, groundwater salinization, coastal aquifers, small islands

01

Introduction

One of United Nation's sustainable development goals is to provide clean water and sanitation for all (SDG 6) by ensuring clean and affordable access to drinking water and implement integrated water resources management (United Nations, 2019). Small islands such as Delft Island, Sri Lanka, rely on groundwater as the main source of freshwater for various purposes (Falkland & Custodio, 1991). On these islands, groundwater typically occurs as thin layers of convex-shaped freshwater lenses floating above seawater in phreatic aquifers (White & Falkland, 2009). Frequent occurrences of natural threats such as drought (Presley, 2005; White *et al*., 2007), typhoons, storm surges, and tsunamis (Kench *et al*., 2006; Terry *et al*., 2010), coupled with anthropogenic pressures including over-extraction of groundwater and water contamination (White *et al*., 2007; White & Falkland, 2009) make island aquifers among the most vulnerable groundwater systems in the world. Saltwater intrusion is one of the prevalent threats to groundwater resources, and it can occur both vertically and laterally. It is mostly caused by overexploitation and storm surges on islands with low elevation, and is expected to be aggravated in the future due to the anticipated sea level rise (Barnett *et al*., 2003; Woodroffe, 2008; Polemio & Walraevens, 2019).

> *"Frequent occurrences of natural threats coupled with anthropogenic pressures including over-extraction of groundwater and water contamination make island aquifers among the most vulnerable groundwater systems in the world"*

Several studies (e.g. White *et al*., 2002; Aris *et al*., 2007; Praveena & Aris, 2009; White & Falkland, 2009) have shown that hydrochemical characterization, combined with geophysical and isotopic analysis, can provide information on the FWL of small islands (e.g. lens thickness and water types), as well as the key processes influencing the main composition of groundwater. Moreover, the use of numerical modelling for water management and decision-making has been applied to many islands (Werner *et al*., 2017). Studies on groundwater abstraction and the resulting impacts of saltwater intrusion (using versions of the SEAWAT model) have been performed e.g. Abdullah *et al*. (2010), Banerjee and Singh (2011) and Post *et al*. (2018) for atoll islands. Banerjee and Singh, (2011) focused on the optimization of pumping rates and recharge in the Lakshadweep Archipelago, India. Results showed that an increase in pumping rate due to increasing demands could result in a greater threat of saltwater intrusion unless countered by a higher recharge, which can be achieved through artificial recharge. Post *et al*. (2018) also showed the contraction of FWL due to pumping.

Scarcity of reliable freshwater impedes further socio-economic development of small and low-lying islands (Duncan, 2012), which is the case for Delft Island (Goonatilake *et al*., 2013) and its tourism. Visitors are predominantly short-stay, which results from the lack of accommodation and facilities for tourists (Wijayawardene *et al*., 2015). Despite a relatively high amount of precipitation during the wet season, reports by the locals seem to indicate the presence of shallow saline water. Furthermore, the lack of understanding of the spatial distribution of the island's freshwater lens, combined with inadequate knowledge on the role of recharge and abstraction on freshwater distribution, and insufficient data on water usage, hinders the formulation of a sustainable aquifer management plan to meet the present and expected future domestic water demand. Studies have been conducted to develop scientifically-based water resource management policies in small pacific islands with limited availability of data, which includes a methodology for vulnerability assessment of freshwater (Duncan, 2012), development of indicators for groundwater vulnerability (Holding *et al*., 2016), and estimating the FWL volume of atoll islands through algebraic models (Bailey & Kivi, 2017), among others.

The main objectives of the current research are to 1) evaluate the spatial distribution of fresh and saline groundwater and assess its sensitivity to recharge and hydraulic parameters; and 2) explain the processes governing groundwater chemistry on Delft Island, Sri Lanka. This research includes the impact of anthropogenic activities and natural events on FWL formation and degradation. Sustainable and adaptable management methods will be proposed to mitigate the negative impacts and meet the freshwater requirements of a growing population under climate change.

02

Study Area

Locally known as “Neduntheevu”, Delft Island is located in the Palk Strait found between the northern province of Sri Lanka (Jaffna District) and the Tamil Nadu state of India.
It is the second-largest island in Sri Lanka having an extent of approximately 50 km^2 with a maximum length of 8 km and a maximum width of 6 km. Delft Island is situated in Sri Lanka’s dry zone with annual precipitation ranging from 696 mm to 1,125 mm per annum, 80-90% of which occurs during the wet season of October to January (Goonatilake *et al*., 2013).
The climate is semi-arid and the vegetation cover of the island is mainly tropical trees and plants dominated by Asian Palmyra Palms, Phoenix thorny shrubs, and grasses that thrive on the island’s coralline soil. Most of the area in the island has an elevation between 1 and 2 meters above mean sea level (masl) with the highest elevation of approximately 6 masl. Two major lakes are situated in the central area with various ponds and waterholes scattered throughout the island.

Delft Island is one section of the geological formation that makes up Jaffna peninsula. The geological map of Delft Island, displayed in Figure 7-1 highlights Quaternary sand deposits from recent to the Pleistocene period (Qrsb, Qpsyb), overlying Tertiary Vanathavillu limestone formations (Tmsl); the latter is generally 100 to 150 m thick, well jointed, distinctly bedded and highly karstified.

Groundwater is the main source of freshwater to the ~5,000 residents of Delft Island. The estimated demand, ranging from 250 to 500 m^3/day based on WHO recommendations (OHCHR, 2010), is abstracted from 50 or more shallow hand-dug wells, which are scattered throughout the island (Goonatilake *et al*., 2013). There are two major wellfields on the island, namely the Manatharai and Saraapiddy Wellfields (Figure 7-1) that are freely accessed by locals. The Saraapiddy Wellfield is located in the southwestern part of the island with coral limestone as the main geological unit of the aquifer. The Manatharai Wellfield is situated in a shallow sandy aquifer located in the northeast area and is less than 75 m from the shoreline. Each wellfield has an approximate area of 15,000 m^2 or 0.015 km^2 and has 12 wells unevenly distributed over the area.

Abstractions are currently unmonitored and unregulated, thus information on its quantity and quality are mainly from discussions with locals and individual studies on the area. Despite having two major wellfields on the island, many

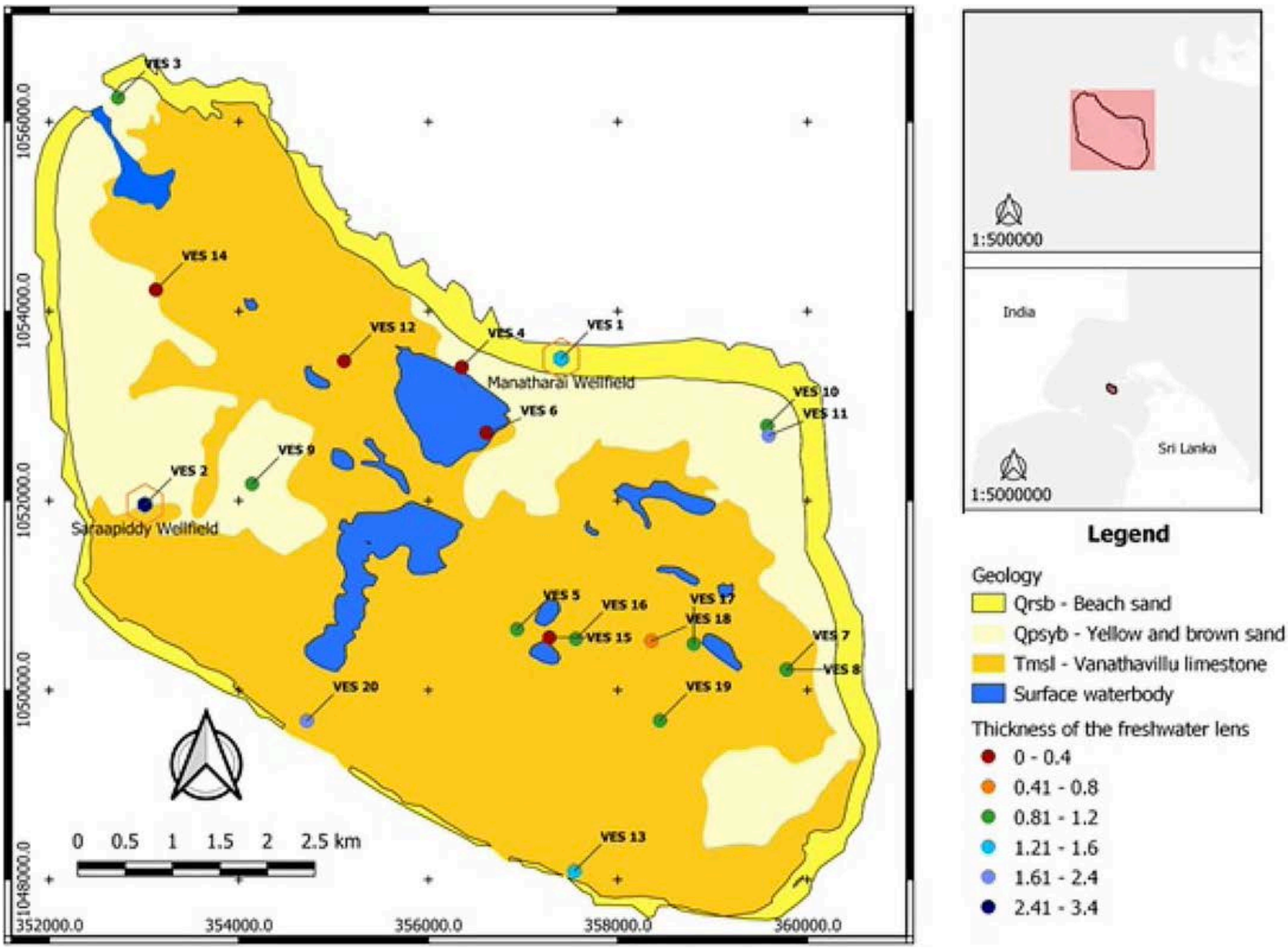


Figure 7-1 *Geological map of Delft Island, showing VES Survey sites and corresponding lens thicknesses(map modified from Geological Survey and Mines Bureau (GSMB) of Sri Lanka, 2002)*

villages have insufficient freshwater to meet their demands. The Saraapiddy wellfield is reported to have the best water quality and serves many of the neighbouring villages (Wijayawardene *et al*., 2015). However, discussions with locals highlight that wells, both within the wellfield and around the island, turn brackish during the dry season. Results from a groundwater quality study of the Jaffna Peninsula further reflected microbiological and chemical contamination (Mahagamage *et al*., 2019). High nitrate concentrations were particularly observed in some samples and were primarily attributed to intensive agricultural practices (Jeyaruba *et al*., 2009, Sutharsiny *et al*., 2014, Vithanage *et al*., 2014).

Currently, to mitigate the impacts of water scarcity, water supply is supplemented by the Sri Lanka Navy, who provide water to the residents using reverse osmosis (RO) technology (Wijayawardene *et al*., 2015). There are no known strategies in place to manage the water quality issues experienced on the island.

Another user of water on the island is the agriculture community. Crop cultivation is performed primarily during the "maha" season (September to March). Though not focused on in this paper, water quality and quantity issues, which affect domestic users, also affect agricultural practices (Wijayawardene *et al*., 2015).

"There are no known strategies in place to manage the water quality issues experienced on the island"

03
Methods

The field assessment of Delft Island consisted of geophysical surveys, field observations, discussions with the locals, and water sampling from wells and lakes for chemical and stable isotope analysis, to provide further insight into the occurrence of groundwater and the distribution of the fresh and saline waters on the island. Fieldwork was carried out during the period 22 November – 25 December 2019, coinciding with the northeast monsoon period and followed by data processing and interpretation, as well as the construction of conceptual and numerical models.

3.1. Vertical Electrical Sounding

In this study, 20 one-dimensional (1D) Vertical Electrical Sounding (VES) surveys (Figure 7-1) were completed in the field using the low-cost Volterra III device developed by Practica Foundation. The surveys were completed using the Schlumberger configuration array in two (2) areas and the Wenner configuration array in 18 areas, with both arrays employed in one area for a comparison of results.

To attain resistivity values during each survey, an electrical current is injected into the earth by two current electrodes (A and B), and a current is measured by two intermediate potential or measuring electrodes (M and N). Readings of both the potential differences from the measuring electrodes and the current strengths at the current electrodes enable us to determine the apparent resistivity of the rock. As the spacing increases between current and measuring electrodes, so does the penetration depth of the current. Apparent resistivity reflects the combination of the material porosity, pore size and shape, density, water quality, water content and temperature (Todd, 1980).

The maximum current electrode configuration (AB/2) ranged from 30 to 75 m. Limitations to the execution of electrical resistivity surveys included restrictions in the area due to built-up coral walls, the thick density of Palmyrah Palms in some areas, coral limestone outcroppings which hinder the insertion of electrodes, and the inundation of flat or low-lying areas. The preliminary interpretation of the VES curves was carried out by the curve matching technique, where field curves are matched with theoretical master curves (Bhattacharya *et al*., 1968; Orellana & Mooney, 1966). The technique used to translate apparent resistivities into layer resistivities and thicknesses is curve fitting or the mathematical inversion technique. Field curves were completed using GEWin-Excel software developed by van der Moot (2020). During interpretations, water levels and electrical conductivity (EC) measurements from nearby wells were used as indicators of soil saturation depths and degree of salinity respectively.

The EC measurements collected from some wells assigned for domestic use on Delft Island exceeded the World Health Organisation (WHO) drinking water quality standards for total dissolved solids (TDS) (mg/L) or its equivalent EC (µS/cm) in freshwater (WHO, 2017), which is summarized in Table 7-1. Table 7-1 includes an additional classification for "useable water" with an upper limit of 5,000 µS/cm EC for this study. This value accounts for the upper limits of EC values measured in the wells in the area and is further used as an intermediate stage between fresh and saline water in the interpretation of the VES surveys performed on Delft Island. The corresponding limit of 2 Ωm for porewater resistivity (see equation 7-1) can be considered an approximation of the extent of the FWL since VES surveys were performed during the recharge period. Thus, pore-water resistivities of 2 Ωm and 0.7 Ωm are calculated for brackish and saline waters respectively in VES interpretations. TDS is converted to EC using the calculation TDS = EC (µS/cm) x 0.7.

Table 7-1 Water quality classification based on WHO standards for water quality including a range for TDS [mg/L] measurements observed in drinking and domestic wells on Delft Island

Water classification	TDS range [mg/L TDS]	EC range [µS/cm]
Fresh	< 1,200	< 1,714
Useable water[1]	< 3,500	< 5,000
Brackish	3,500 – 9,999	5,000 – 14, 284
Saline	≥ 10,000	≥ 14, 285
Seawater and brine	≥35, 000	≥ 50,000

[1]As defined for this study

$$F_R = \ell / \ell_w \qquad \text{Equation 7-1}$$

The Formation resistivity factor, FR reflects the relation of the total resistivity of the geological layer or formation(ℓ)and the pore-water resistivity ℓ_w.

3.2. Water Sample Collection

The physicochemical properties of 57 water samples (26 groundwater and 31 surface water) were measured in the field. Properties measured include temperature, electrical conductivity (EC), dissolved oxygen (DO), pH, and alkalinity (HCO_3^-), as well as the nitrate concentration (NO_3^-) using test strips. We used Greisinger portable digital conductivity meters (model GMH 3430) to measure EC and temperature, WTW pH 323 and pH 340i meters for pH, and the WTW Oxi 3310 meter for DO. The HACH titration test kit was used to determine the alkalinity in the field through sample titration with hydrochloric acid as the titrant and bromocresol green/methyl red as the indicator. The recorded units were converted to HCO_3^- concentration using the relationship: 100 digits = 122 mg/L HCO_3^-.

Furthermore, a total of 29 groundwater and 12 surface water samples, as well as one rainwater and one seawater sample were collected and kept in cold storage for laboratory analysis of cations (Na^+, K^+, Mg_2^+, Ca_2^+, total Al, Mn, and Fe) and anions (Cl^-, PO_4^{3-}-P, SO_4^{2-}, and NO_3^--N), and stable water isotopes ($\delta^{18}O$ and δ^2H). The standard procedures for groundwater and surface water sampling were observed in the field, which includes filtering of water, and pre-acidification of sampling bottles for cation analysis (IAEA, n.d., ASTM, 1982; US EPA, 1983; Appelo & Postma, 2005).

The concentrations of cations and anions were analysed in the laboratory of IHE Delft following standard procedures, using Inductively Coupled Plasma - Optical Emission Spectrometry (ICP-OES) and Flame Atomic Emission Spectroscopy (FAES) for cations, and Ion Chromatography System (ICS) for anions. Additionally, the concentration of deuterium (δ^2H) and Oxygen-18 ($\delta^{18}O$) were determined using the liquid-water isotope analyser which utilizes the Tunable Diode Laser Absorption Spectroscopy (TDLAS) principle (APHA, 2005). The concentrations are expressed in per mil (‰) and are denoted by δ since the measured values are written relative to a known standard which is the Vienna Standard Mean Ocean Water (VSMOW) isotopic ratio standard (IAEA, n.d.). The analyser used for isotope measurements has an accuracy of 0.2 ‰ for $\delta^{18}O$ and 0.6 ‰ for δ^2H. Mineral saturation indices (SI) and partial pressure of CO_2 were calculated using PHREEQC.

3.3. Hydrochemical Analysis

Several scatter plots of relevant physicochemical parameters were generated to identify relevant ion sources and hydrochemical processes. Furthermore, the δ^2H and $\delta^{18}O$ compositions (‰) of rainfall, surface water, groundwater, and seawater samples were plotted along with the global and local meteoric water lines (IAEA/WMO, 2020). The local evaporation line is based on the isotope compositions of the evaporated rainwater samples collected using an uncovered rainwater collector, during the field assessment. Moreover, the $\delta^{18}O$ composition (‰) of samples was plotted against Cl^- (mmol/L) using a log-normal distribution to determine the possible effects of evaporation (Rayleigh fractionation) and seawater mixing (conservative line). The range of conservative seawater mixing line was established using the linear relationship of the upper end-member, based on the VSMOW concentrations of Cl^- (566 mmol/L) and $\delta^{18}O$ (0 ‰) in seawater, and the two lower end-members based on the measured concentrations of Cl^- with the least effect of evaporation (Celle *et al.*, 2004). The seawater mixing line was extrapolated until it intersected with the Rayleigh fractionation line for rainwater samples to determine the theoretical end members indicated by no mixing of seawater (conservative). Additionally, the fraction of seawater (fsea) in a sample was calculated through mass balance based on the concentration of Cl^-. Chloride was used to determine the seawater fraction in the freshwater since chloride exhibits little fractionation in seawater and freshwater (Appelo & Postma, 2005).

Additionally, to determine the location of samples affected by evaporation and salinization, a system of classification through geographic visual representation was developed for this research using Cl^- and δ^2H. Figure 7-2 shows the symbol for the dominant water source (end-members) used in the classification and the corresponding description. This classification is based on the assumption that the only source of Cl^- ions are rainwater and seawater, with possible enrichment through evaporation. It must be noted that the classification corresponds to the prevailing hydrochemical processes and does not indicate the overall composition of the water samples.

3.4. Conceptual Model

The conceptual model of the freshwater lens in the Saraapiddy wellfield in Delft Island was developed by combining the results from recharge assessment (Wu, 2020), measured groundwater levels for flow pattern and direction, vertical electrical sounding measurements, in-situ measurements of surface and groundwater parameters for lens thickness, and hydrochemical and isotope analysis for the identification of the governing hydrochemical processes, as well as possible contaminations.

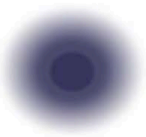
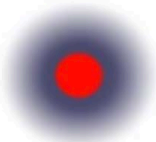
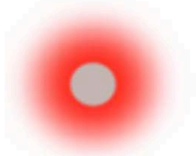
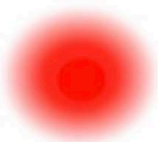
Symbol	Type	Description
	Rainwater Dominant	The large blue circle indicates Cl^- concentration of 0.3 to 12 mmol/L while the small blue circle indicstes δ^2H concentration of -41 ‰, which is the composition of freshwater in the island.
	Evaporation Dominant	The large blue circle indicates Cl^- concentration of 0.3 to 12 mmol/L while the small red circle indicstes δ^2H concentration of -17 ‰, which is the composition of freshwater in the island.
	Salinization Donimant	The large red circle indicates Cl^- concentration of 110 to 566 mmol/L while the small grey circle indicstes δ^2H concentration of -3.5 ‰, which is the composition of saline water in the island.
	Mixed Evaporation-Salinization	The large red circle indicates Cl^- concentration of 110 to 566 mmol/L while the small red circle indicstes δ^2H concentration of -17 ‰, which is the composition of both evaporation and saltwater mixing.

Figure 7-2 Description of the three end-member classifications of water samples (rainwater-evaporation-saltwater) used for spatial distribution analysis.

3.5. Numerical Modelling

The SEAWAT program was used to simulate the dynamics and mixing processes of the fresh-saltwater interface. SEAWAT is a coupled model based on the three-dimensional (3D) finite-difference flow model MODFLOW (Harbaugh *et al*., 2000; McDonald and Harbaugh, 1988) and transport model, MT3DMS (Zheng and Wang, 1999). It was developed to simulate three-dimensional, variable-density, transient groundwater flow in porous media (Guo & Langevin, 2002). The methodology for this study can be found in Banerjee and Singh (2011); Calvache and Pulido (1994); Langevin and Guo (2006).

The above-mentioned hydrogeological information is the basis of the conceptual model from which the numerical groundwater model was developed. The island is simulated as a three dimensional-mesh that represents an area of 82.8 km^2 and the maximum thickness of the aquifer is 25.5 m. The thickness of the aquifer extends to 19.5 m below the maximum elevation of the island. The aquifer is divided into twenty (20) layers. Layer one is the thickest and extends from the surface to -1.0 m below sea level, layer two (2) is 0.5 m thick and layers three (3) to twenty (20) are each 1.0 m thick. FWL thickness at a specific location is considered as the combination of groundwater heads h [m] and the depth of the fresh-saltwater interface, H [m].

The fresh-saltwater interface and its dynamics were recreated by assigning a constant head boundary to layer two, at the fringes of the island, where the elevation is 1 m below sea level. This reflects discharges to the ocean through the outflow zones, where the water table and interface intersect (Dose *et al*., 2014). Layer 2 was chosen to allow the recharge to enter the aquifer before discharging to the sea. A no-flow boundary is assigned to the cells adjacent the fringe of the island, which extends from layers 3 to 20. The sea acts as a constant concentration boundary (ICBUND) for the confined layers (2 to 20) and the top layer of the aquifer is unconfined.

After calibration, this numerical model assumes a homogeneous and anisotropic aquifer with three components of the water balance; the inflow from recharge, f, the outflow due to abstractions, and exchanges between the FWL and sea at the constant head barrier. Desktop studies revealed a dearth of existing data for the study area and the field assessment resulted in limited data for developing a representative base model that fully accounts for the hydrogeological processes observed and inferred during the field assessment. Thus, this simplified numerical model aimed to recreate the uninterrupted development of a freshwater lens on Delft Island using field data, literature values from studies completed in similar hydrogeological environments, and the Ghyben-Herzberg (G-H) analytical solution (Ghyben, 1889; Herzberg, 1901), before proceeding with four hypothetical scenarios (see corresponding section below).

This simplified model does not account for heterogeneity, unevenly distributed recharge, and the saline ponds at the centre of the island, which were observed during the field assessment and integrated into the conceptual model. The impacts of hydrogeological parameters on the spatial distribution of fresh and saline waters were assessed individually in Craig (2020), as different scenarios to recreate the irregularly shaped FWL.

The evolution of the freshwater lens was simulated using a steady-state model on a homogeneous and isotropic aquifer; and the only flow package activated was recharge, which was evenly distributed. The slope that relates fluid density (ρ) to concentration (DRHODC) is assigned a value 0.0007143 and is equivalent to .

For steady-state calibration, the trial-and-error approach was used until a comparable thickness of the freshwater lens was attained. At its thickest, the calibrated thickness is greater than the FWL thickness measured on the island as outflows, from abstractions and to surface ponds are excluded.

Table 7-2 *Parameters for homogeneous and anisotropic simulations to assess abstraction potential*

Parameter	Value
Effective porosity, ne	0.35
Longitudinal dispersivity	5 m
Horizontal transverse dispersivity, αTH /αL	0.1 m
Vertical transverse dispersivity, αTV /αL	0.02 m
Constant head concentration	35,000 mg/L
Recharge, f (10% of annual mean rainfall)	$2.05x10^{-4}$
Horizontal hydraulic conductivity, kh	25 m/day
Anisotropy, kh/kv	100
Courant number	0.95

Table 7-3 *Parameter values used for sensitivity analysis*

Parameter	Value
Recharge, f	5% (half), 20% (double)
hydraulic conductivity, kh	12.5 m/day (half), 50 m/day (double)
Anisotropy, kh/kv	10%
Vertical transverse dispersivity, αTV /αL	0.01, 0.02, 0.05 m
Longitudinal dispersivity, L	10 m

Listed in Table 7-2 are the parameters for homogeneous and anisotropic simulations to assess the abstraction potential and the impacts of abstractions.

3.5.1. Sensitivity Analysis

For the sensitivity analysis, both groundwater heads and salinity levels from the final calibration were used as the reference values for comparison. The sensitivity of the thickness of the FWL to recharge and hydraulic conductivity and its anisotropy and the mechanical dispersivity were evaluated. Parameters and the values used in the sensitivity analysis are displayed in Table 7-3.

3.5.2. Scenarios

The developed simplified model simulates the evolution of the freshwater lens in undisturbed conditions and TDS concentrations are not an accurate representation of values observed during the field assessment. Despite the limitations, the values are useful to assess relative changes.

To assess the abstraction potential of the island, the wells included in the model are initially distributed as observed during the field assessment. The simulation period is roughly 20 years (7,200 days based on the 360-day year used throughout the modelling section). For practical purposes, the locations evaluated are the Manatharai and Saraapiddy Wellfields, which have the highest average concentration of wells (2 wells per cell or 2,500 m^2) and serve the majority of residents on the island. Additionally, a hypothetical wellfield placed on the inner part of the island is assessed.

The number and concentration of wells in the hypothetical wellfield are similar to the Manatharai and Saraapiddy wellfields; 12 wells in total and 2 wells per cell. This hypothetical wellfield represents the redistribution of 12 wells observed on the island and the total number of wells in the simulation does not exceed the number of wells observed during the field assessment. At its location, the depth of the fresh-saltwater interface is at 3.5 m below sea level and similar to the thickest area of useable water interpreted from VES measurements.

TDS concentrations from simulations are averaged for each area, to reflect the impacts on the FWL when the minimum recommended daily water volume for residents is met by abstractions from the current distribution of wells (Scenario A) and the ability of the FWL to recover from abstractions in Scenario A (Scenario D). Water requirements per resident are calculated based on the WHO recommendations of 0.05 to 0.1 m^3 (50 – 100 L) per day (OHCHR *et al.*, 2010). Scenarios B and C reflect the impacts of changing the method of abstraction to a distributed method using horizontal or skimming wells. Skimming wells are wells which abstract freshwater from the upper zone of an FWL or a fresh-saline aquifer (Woodroffe & Falkland, 2004; Rao *et al.*, 2006; 2007; White & Falkland, 2009). The volume of water abstracted in Scenario B meets the minimum daily water requirements whereas Scenario C meets the max imum daily water requirements for the current population of Delft Island.

Table 7-4 Simulation modelling for different scenarios

Simulation	Description
Scenario A	Abstractions at 36 wells, 18 cells, 5 m^3/d per well for 7,200 days
Scenario B	Abstractions at 180 wells, 180 cells, 1 m^3/d per cell for 7,200 days
Scenario C	Abstractions at 180 wells, 180 cells, 2 m^3/d per cell for 7,200 days
Scenario D	Recovery after pumping at 5 m^3/d per well for 7,200 days

04

Results and Discussion

4.1. Curve Fitting and Interpretation of VES Data

Results from VES surveys show apparent resistivity, ρa, decreasing with depth, which indicates higher salinity levels at greater depths (Figure 7-3). Field curves reflect a double descending type Q curve and four (4) geo-electric sections or geological layers, in most instances.

Interpretations reflect a thin irregularly shaped (Figure 7-4) freshwater lens on Delft Island that is thickest in the Tmsl limestones of the Saraapiddy wellfield at VES 2 (3.3 m) and Qpysb sands found at VES 11 (2.1 m). The lens is thinnest or absent in the brackish waters of VES surveys 4, 6, and 12 (0 m) near the Veddukali Lakes at the centre of the island.

The useable FWL thickness shows variations within the same geological deposits (Figure 7-1). In the Tmsl limestone deposits, the thickness ranges from 0.2 (VES 15) to 1.1 m (VES 5 and 19) in the Nature Conservation Park to non-existent (0 m) at the brackish waters of VES 14. At higher elevations, in the Qpsyb sand deposits, it ranges from 0.8m (VES 3) to 2.1 m (VES 11). In the Qrsb beach sand deposits, the useable water in this soil type ranges from 1.3 m for VES 13 to 1.8 m at VES 20, both of which are on the southern coast of the island. In comparison, VES 1 on the north coast, shows a thickness of 1.4 m.

Additionally, FWL thicknesses show a poor correlation to distance from the sea or the saline ponds at the centre of the island but the relationship between elevation and thickness is maintained. This infers that there could be pockets of saline water, embedded in the limestone. Hence, variations in thickness can be due to limestone heterogeneity resulting from differences in porosity, interconnectivity or permeability.

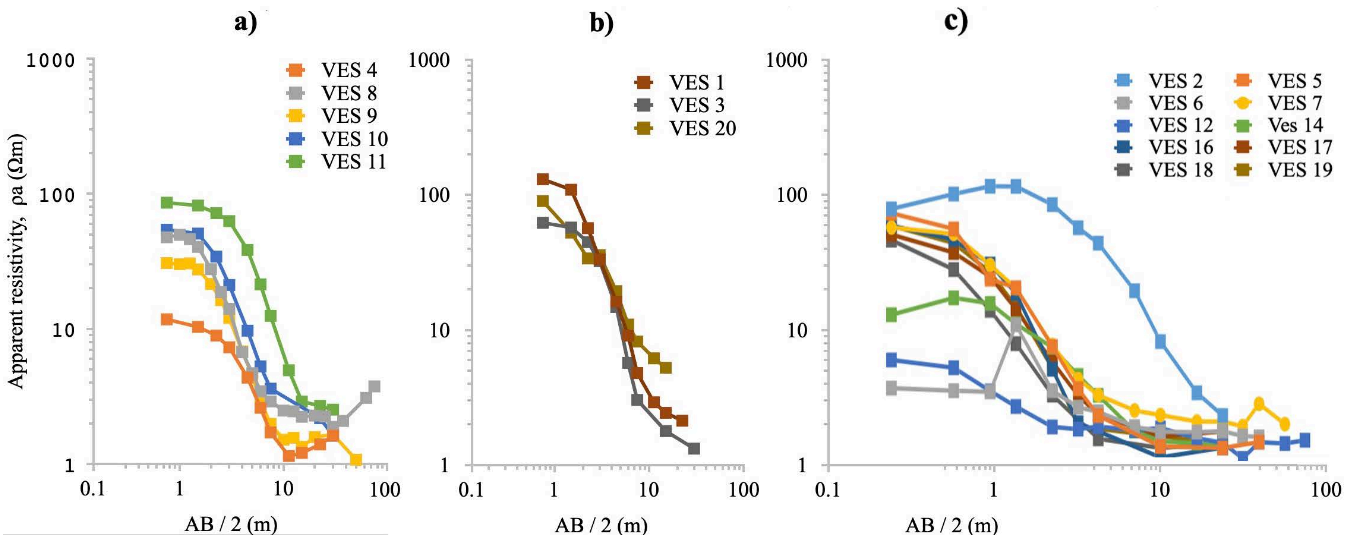
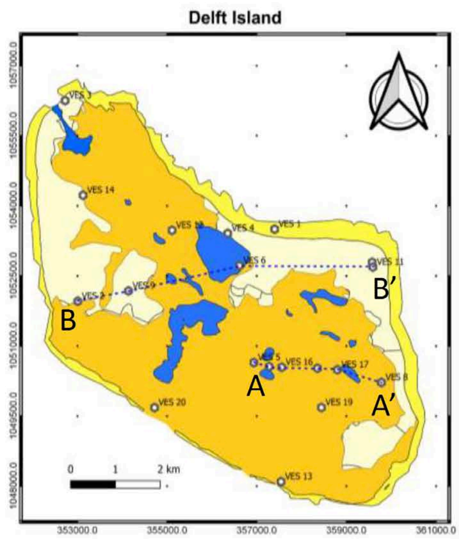


Figure 7-3 *Geological map of Delft Island, showing VES Survey sites and corresponding lens thicknesses(map modified from Geological Survey and Mines Bureau (GSMB) of Sri Lanka, 2002)*



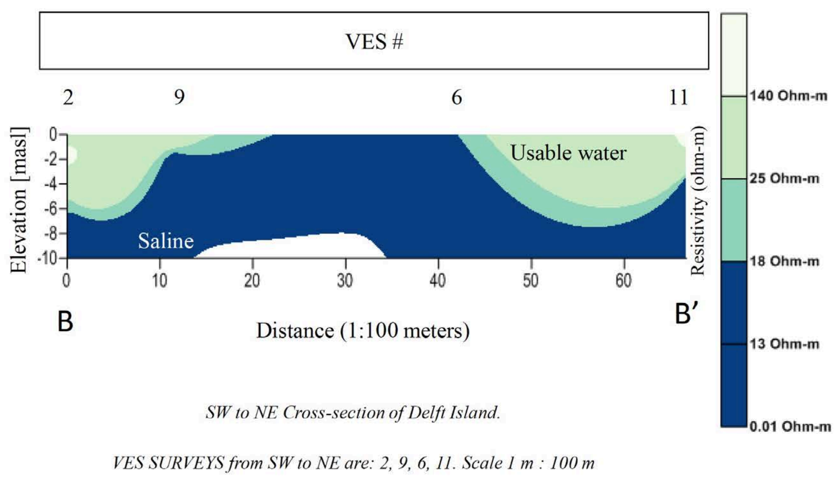


Figure 7-4 *2D VES Resistivity Map*

4.2. Hydrochemical Analysis

The source isotope composition of the evaporated rainwater samples is approximately -5.5‰ δ²H and -33.8‰ δ¹⁸O. The δ²H and δ¹⁸O composition (‰) of groundwater samples ranged from -41 to -15.1 ‰ and from -6.9 to -3.33 ‰, respectively, while that of surface water samples ranged from -17.5 to 2.6 ‰ and from -2.51 to -0.65 ‰, respectively. Figure 7-5 shows that the surface water samples are more enriched in heavier isotopes as compared with the groundwater samples. Furthermore, the surface water samples are located near the meteoric water lines with a slight offset to the right adjacent to the local evaporation line.

The seawater sample has an isotopic signature that is similar to the surface water samples, suggesting possible intrusion of marine waters to ponds and lakes. On the other hand, the scatter of groundwater samples around the meteoric water lines in the field constituting the probable source composition of the evaporated rainwater samples reveal their meteoric origin (Saxena *et al.*, 2014; Hiscock & Bense, 2014; Appelo & Postma, 2005). Moreover, the relatively depleted composition of the groundwater samples suggests preferential recharge during heavy showers in the wet season, when rainfall isotope composition is relatively depleted (Han *et al.*, 2014).

Evaporation and mixing with saltwater affect the location of the samples on the plot and can be better assessed by plotting δ¹⁸O (‰) vs. Cl^- (Figure 7-6). Most of the surface water samples have enriched isotope concentrations due to evaporation as observed from the Rayleigh fractionation line (Figure 7-6). The increase in Cl^- concentration seems most primarily caused by mixing with seawater.
On the other hand, most of the groundwater samples plot within the range of conservative seawater mixing line, which suggests that the increase in Cl^- concentration was mainly due to the mixing of groundwater with high salinity water (salinization). Notwithstanding, some groundwater samples do show quite significant evaporation, linked to either groundwater recharge processes or exposure to the atmosphere through the wells, or a combination of both. For instance, rainfall water might have ponded and undergone evaporation before infiltration and recharge, resulting in a more enriched isotopic composition.

Figure 7-7 also reveals that groundwater salinization is predominantly linked to mixing with seawater and that this process has mostly occurred in residential areas, low-lying areas, near the lagoons and the coast. Salinization, therefore, is most evident where the freshwater lens is thin and is possibly further enhanced by groundwater abstractions.

In contrast, the surface water samples exhibit the dominance of the mixed evaporation-salinization water type (Figure 7-8). Salinization of surface water can be the result of flooding of seawater, such as the backwater flow from the sea into the ponds through the canals at spring tide. The canals observed during the fieldwork, were constructed by early settlers in

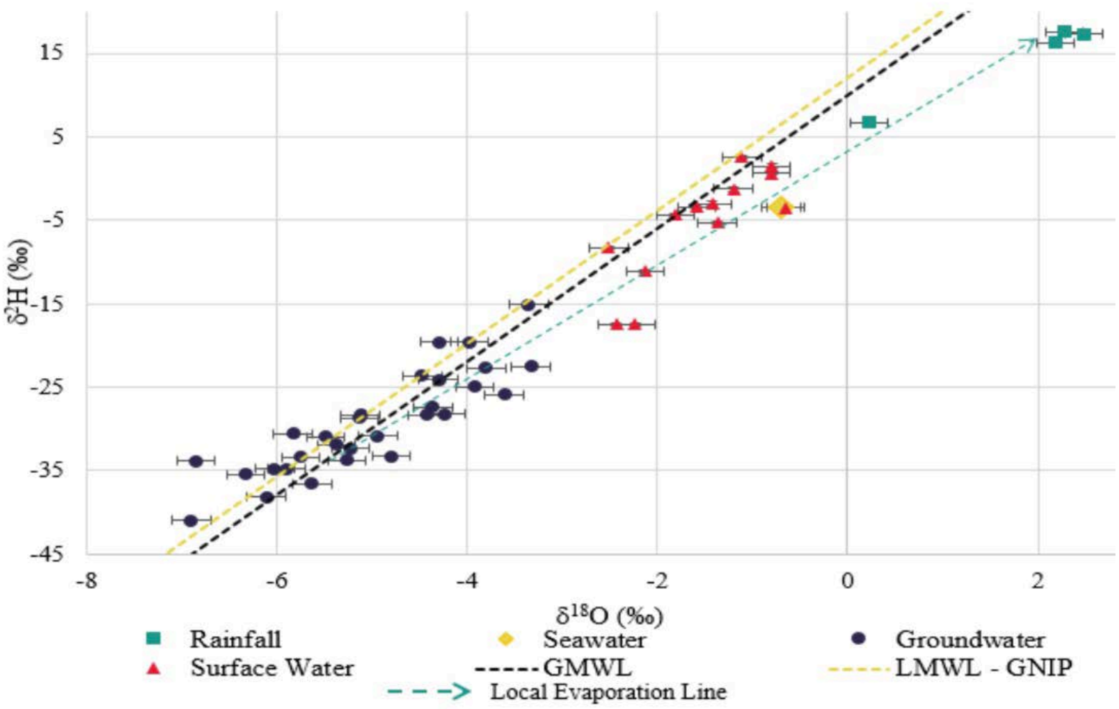


Figure 7-5 *Plot of δ²H vs.δ¹⁸O (‰) of collected water samples, along with the Global Meteoric Water Line (GMWL), Local Meteoric Water Line (LMWL-GNI) and local evaporation line.*

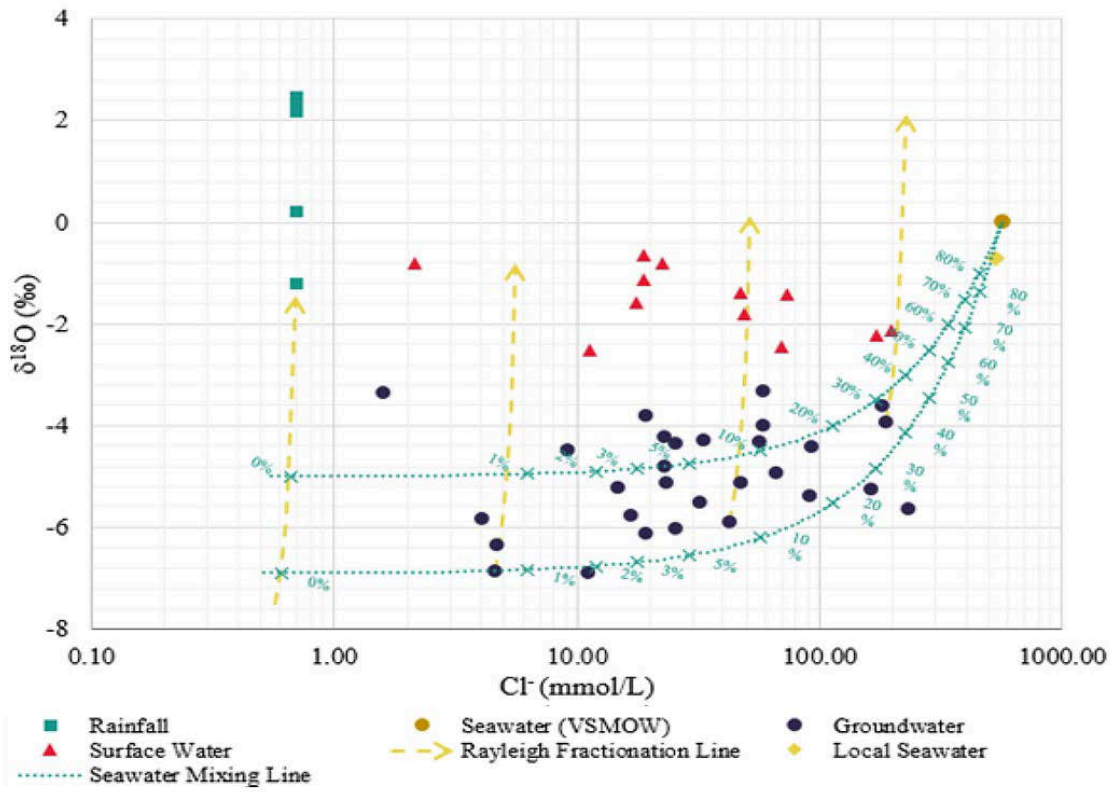


Figure 7-6 *Plot of δ¹⁸O (‰) vs. Cl⁻ concentration (mmol/L) of collected water samples, along with seawater conservative mixing line (VSMOW) and Rayleigh fractionation lines for evaporation*

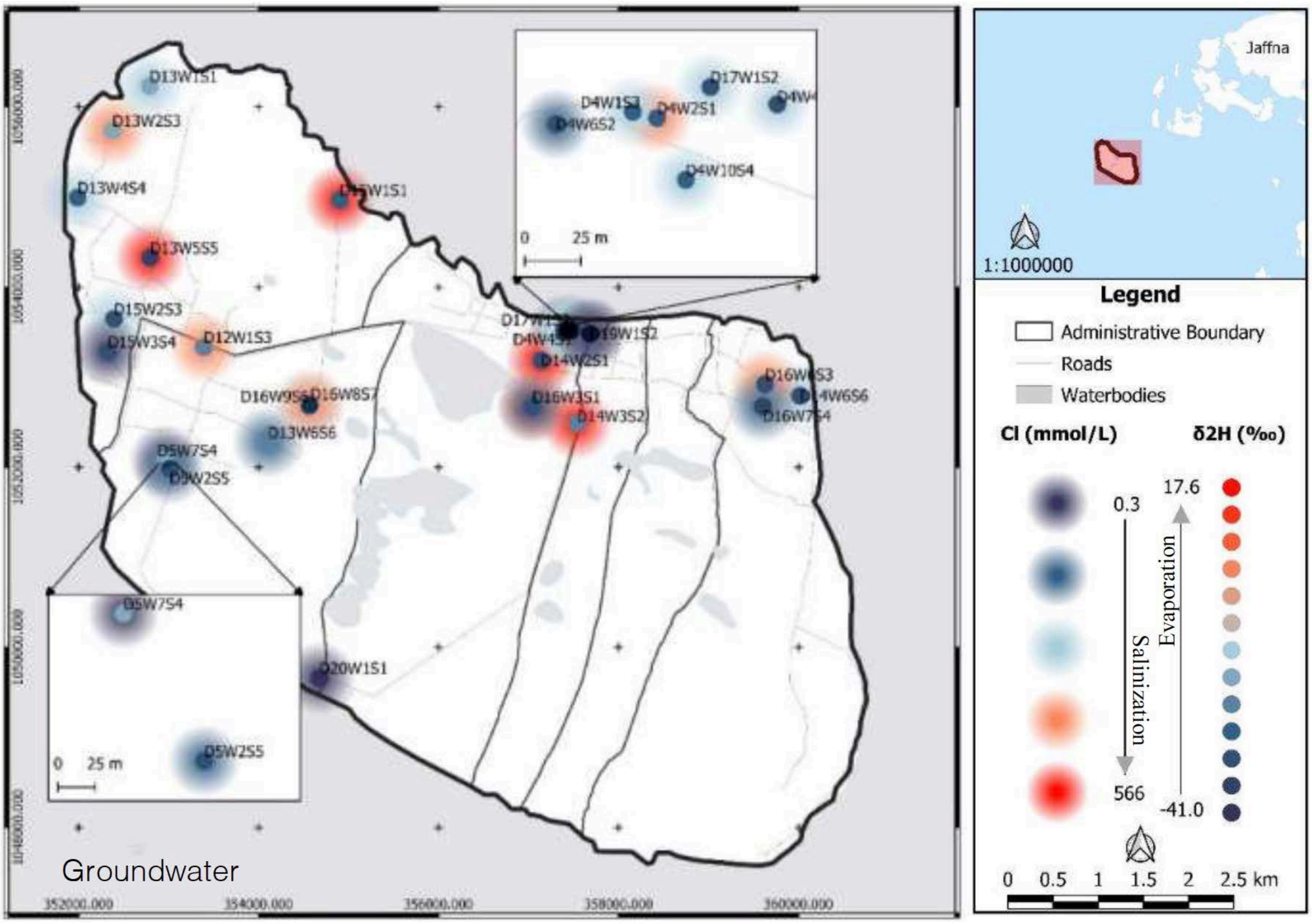


Figure 7-7 *Spatial distribution of the chloride concentration(mmol/L)and δ²H concentration (‰) of groundwater samples showing possible salinzation (logarithmic scale) and effects of evaporation(linear scale)*

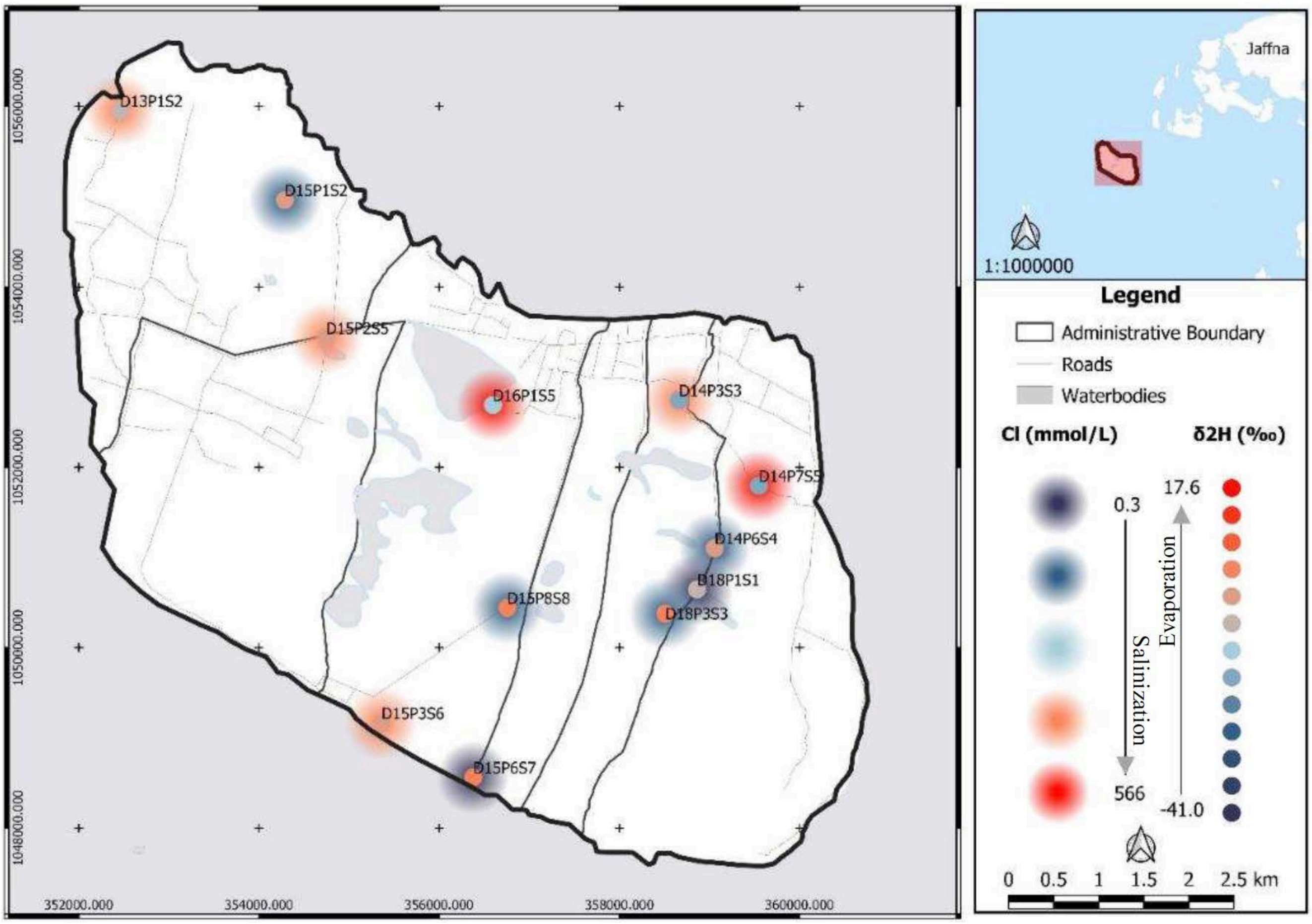


Figure 7-8 *Spatial distribution of the chloride concentration(mmol/L)and δ²H concentration (‰) of surfacewater samples showing possible salinzation (logarithmic scale) and effects of evaporation(linear scale)*

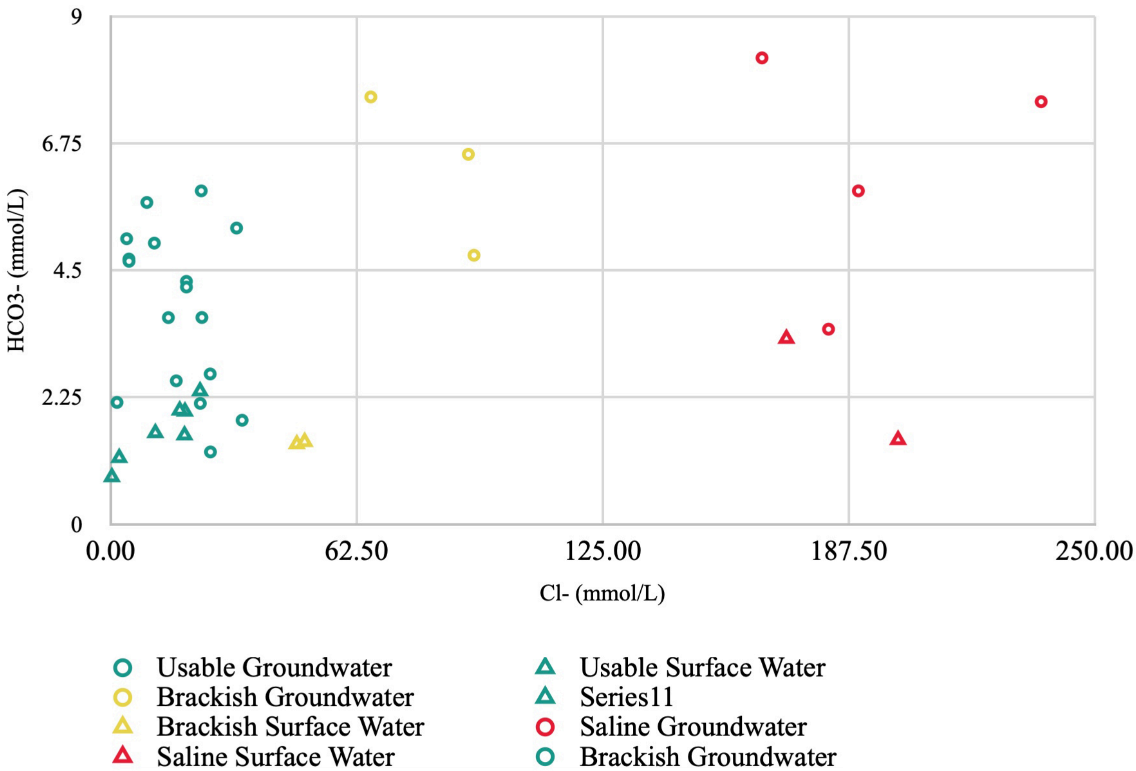


Figure 7-9 *Plot of Cl^- (mmol) against HCO_3^-/Cl^- indicating possible root zone salinization*

the island and serve no specific purpose today, according to local officials. Other possible causes of lake salinization are the intrusion of saline water through surface-subsurface interactions (Werner *et al*., 2013), or vertical forcing of the aquifer caused by tidal fluctuations (Oberle *et al*., 2017).

Saltwater intrusion can also be caused by storm surges, resulting in the inundation of coastal areas and thereby increasing both the salinity of surface and groundwater reserves (Werner *et al*., 2013). Figure 7-9 shows the graph of alkalinity against Cl^- concentration to illustrate the possibility of root zone salinization. High alkalinity in combination with high salinity, as observed in several samples, can be an indication of saline water percolating downward through the root zone following an overwash event, or upward through capillary rise. The latter may occur when a thin freshwater lens is depleted (during dry season) when the available freshwater supply is not sufficient to meet the plant transpiration demand (Stofberg *et al*., 2016), where the water table is sufficiently shallow, or where trees exist with deep roots (such as the Palmyrah palm trees with 1.5 to 3 m rooting depth (Ravichandran, 2018). These factors increase the vulnerability of thin freshwater lenses on low-lying islands as they can have a greater impact on the development of the fresh-saline mixing zone than tidal oscillations (Terry & Falkland, 2010; Wilson *et al*., 2011).

To some extent, the persistent salinity condition of the lakes and the aquifer on Delft Island could also be attributed to the tsunami event in 2004, during which the seawater was reported to have inundated large low-lying areas and to have entered the aquifers through the open wells in a large part of Sri Lanka, including the Jaffna Peninsula. The intruded seawater, due to forced and free convection has vertically mixed in the aquifers rendering the wells unusable and thus prompting the locals to conduct a widespread pumping of wells in some areas in Sri Lanka for days which then resulted to saline water upconing (Llangasekare *et al*., 2006).

4.3. Conceptual Model of the Freshwater Lens

The conceptual model based on the cross-section along the Saraapiddy wellfield is shown in Figure 7-10. The estimated average annual groundwater recharge rates are based on the results of recharge assessment (Wu, 2020), while the flow direction of the freshwater lens is based on the measured hydraulic heads in the wells. Despite the relatively higher rate of groundwater recharge along the coast, the FWL is still thin (about 1-2 m), due to the high aquifer transmissivity and occurrence of tidal mixing, in addition to the processes described in the previous section. Tidal mixing causes loss of freshwater due to salinization from incoming ocean water that leads to an increase in the thickness of the brackish transition zones below the lens (White & Falkland, 2009). Additionally, the freshwater lens generally discharges into the ocean through the "outflow zones" located along the shorelines of the island, causing further loss of the available freshwater (Dose *et al*., 2014). The depicted flow patterns of brackish and saltwater are based on the research of Bryan *et al*. (2017) which suggests a slow circulation of water within the seawater zone resulting in the mixing of fresh and saltwater.

The identified main aquifer type in this cross-section is a limestone aquifer. Due to lack of data in the eastern side of the cross-section (there are no wells in this area), the occurrence of the freshwater lens is uncertain. The elevated EC value of water measured in a nearby well indicates the occurrence of seawater; hence the figure shows no freshwater zone in the area.

Elevated nitrate concentrations were also observed in surface and groundwater samples, which could indicate anthropogenic inputs such as ammonia and manure fertilizers in managed home gardens, and wastewater from domestic septic wastes (Xiao & Gu, 2017). The enzymatic oxidation of NH_4^+, either from excessive fertilizers or manures, results in the production of NO_3^- by nitrifying microorganisms through

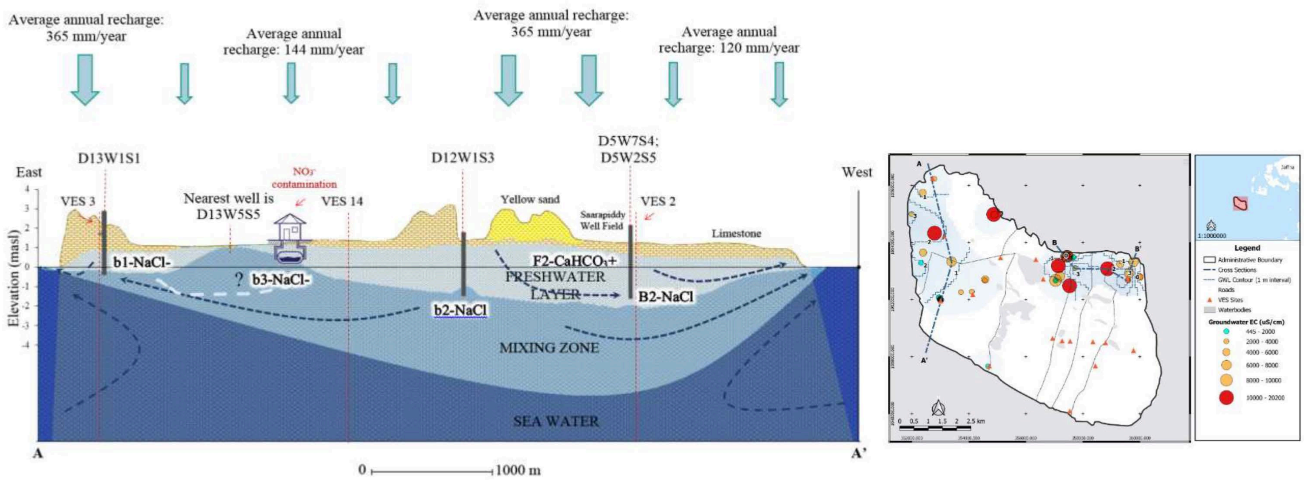


Figure 7-10 *Conceptual model of the freshwater lens based on well data and VES results*

nitrification which can lead to water contamination through leaching (Galloway *et al*., 2008; Zendehbad *et al*., 2019). Additionally, the increase in both NO_3^- and Cl^- concentration might indicate evapoconcentration (e.g. and/or salt in wastewater (Stigter *et al*., 2006), which can be related to the domestic use of brackish water. Elevated levels of NO_3^- beyond the permissible limit of 50 mg/L for drinking water (WHO, 2011) were especially observed in the wells in the Manatharai well field area, based on the strip test results for four wells and the laboratory analysis of two samples.
This wellfield is characterized by the occurrence of an FWL in the shallow sandy aquifer, hence the relatively high infiltration capacity of sand could result in direct infiltration and leaching of any domestic wastewater or agricultural runoff.

An important observation is the elevated concentration of NO_3^- in a nearshore seawater sample, far beyond the typical range of 0.1 to 20 µmol/L in natural seawater (Johnson & Petty, 1983). High nutrient content of groundwater, especially nitrates and phosphates, is a major concern in certain parts of Sri Lanka's coastal aquifers affecting communities and the surrounding coastal ecosystem (Jayasingha *et al*., 2012). This finding is especially alarming for the well-being of the marine flora and fauna around the island, as well as the ecosystem services they provide. Excessive nitrate contamination of seawater has been found to increase coral bleaching, degradation, and coral mortality (Pastore, 2014; Burkepile *et al*., 2020).

4.4. Sensitivity and Scenario Analysis

4.4.1. Sensitivity Analysis

Results from the sensitivity analysis highlight that modelled groundwater heads and FWL thickness are particularly sensitive to variations in recharge and uncertainties in hydraulic conductivity (Figure 7-11). Groundwater heads and FWL thickness increase where there is higher recharge or lower hydraulic conductivity, and vice-versa.
Also, the thicknesses of the FWL and transition zone are very sensitive to changes in the dispersion factors, particularly to the vertical transverse dispersivity, ($\alpha TV / \alpha L$).
Fresh groundwater reserves only appear when $\alpha TV / \alpha L$ is lower than 0.05 and saline waters are deeper as $\alpha TV / \alpha L$ decreases. Lower recharge rates result in fresh and saline waters at shallower depths, despite showing similar thicknesses for the transition zone, when halving recharge.

Overall, the sensitivity analysis shows the responses of the FWL to the changes in parameter values. This gives insights into the uncertainty of the model and highlights where additional monitoring for data is needed, to improve results. Moreover, it shows where model values tend towards interpreted thickness values and the results for parameter values that have been used in other works e.g Banerjee and Singh (2011). These aid in the interpretation of the scenarios and can assist in the decision-making process.

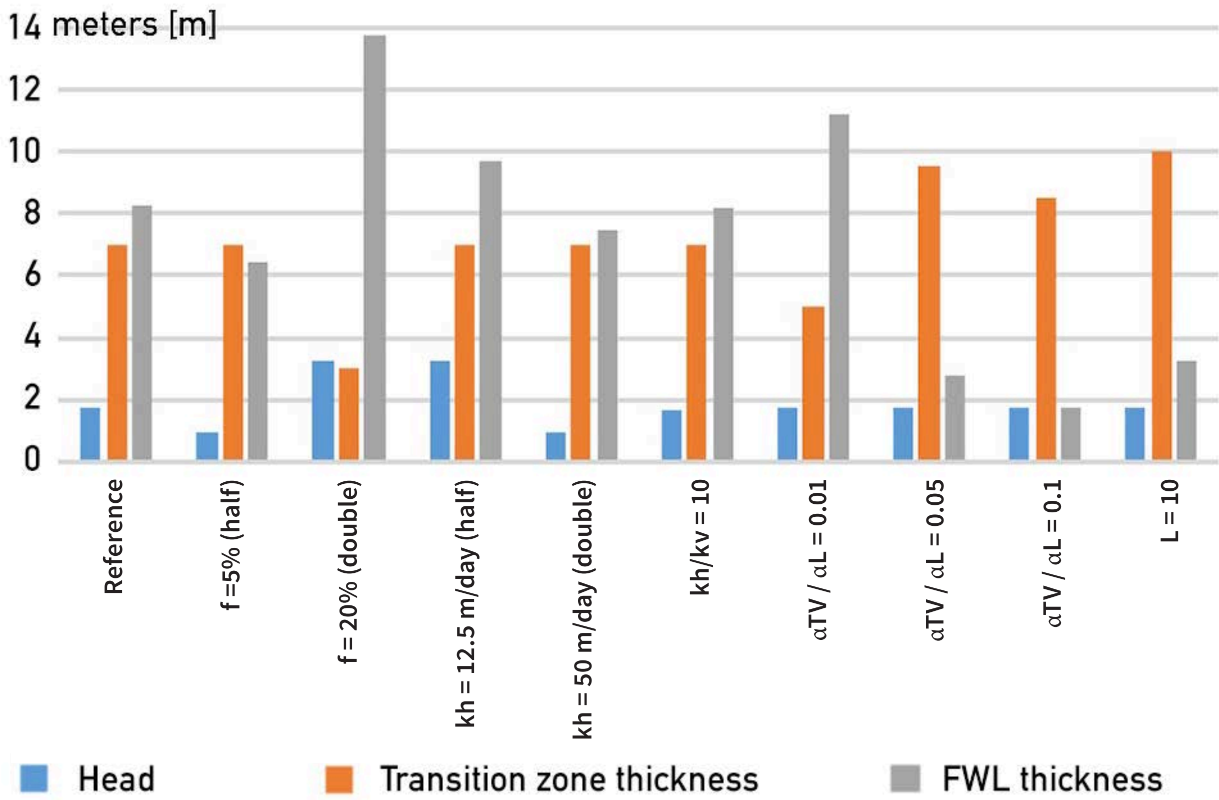


Figure 7-11 *Results of sensitivity analysis of groundwater heads, thickness of the transition zone and thickness of freshwater lens with regard to main parameters*

4.4.2. Scenario Analysis

Table 7-6 displays the average of the results for the four abstraction scenarios. Scenario A highlights that upconing into wells is an imminent threat at all locations, even if the volume of water abstracted only meets the minimum recommended daily water volume for residents. Upconing is most acute in Scenario A (Figure 7-12) which is expected from point source vertical abstraction. Areas with higher initial TDS concentrations or a thinner FWL show greater increases than other locations. The results reaffirm the hypothesis that the distribution of high salinities observed in wells, during the field assessment, can be partly due to localised upconing from abstractions. This is most visible at the Manatharai wellfield.

Results also highlight that the distance from the coast and the depth of the fresh-saltwater interface are influential on the rate of salinization in wells for the same pumping rates, as seen in the Manatharai Wellfield. This aligns with the G-H relationship for a sharp fresh-saltwater interface, where the depth of the fresh-saltwater interface is directly correlated to the groundwater head. The Manatharai wellfield had the highest initial TDS concentrations of all scenarios, which was a consistent result for all measurements collected. Additionally, of the three locations assessed, it has the shallowest fresh-saltwater interface, lowest elevation (sea level) and is closest to the sea (<75 m).

Scenario D highlights that the groundwater reserves do not return to their initial TDS concentrations after pumping has been stopped for 7,200 days and the aquifer is allowed to recharge uninterrupted at steady recharge rates. Based on the sensitivity analysis, the recovery period can be decreased by increasing recharge through managed aquifer recharge, though not a prevalent practice on atoll islands. Uncertainty in climate predictions, due to high variability in rainfall and recharge, in the Pacific and Indian Oceans (Holding *et al*., 2016), may also result in wetter than normal years and recharge exceeding the simulated recharge.The impacts of distributing abstraction over an area, as done in scenarios B and C, results in a slower rate of upconing in wells (Figure 7-12). In comparison to Scenario A, Scenario B results in lower TDS concentrations at all locations when similar volumes of water are abstracted (Table 7-5). Scenario C further highlights the advantages of skimming wells over traditional wells: average TDS concentration in wells is lower than Scenario A despite abstracting twice the volume. Notwithstanding, lateral saltwater intrusion threatens coastal areas for Scenario C (not visible in cross-section). Results show saline water (TDS > 10,000 mg/L) in cells directly north and west, along the coast, of the Manatharai Wellfield up to 250 m away. For all scenarios, the model highlights that the rate of upconing is slowest in areas where the FWL is thickest. Thus, the combination of skimming wells in thicker areas of the FWL can prove to be more sustainable, similar to results obtained by Whitaker and Smart (2004).

Table 7-5 *Average TDS concentrations (mg/L) at observation wells at the end of the model run period for the different scenarios (NB* Usable water is < 3,500 TDS mg/L see Table 7-1 for salinity classification)*

Initial concentrations	Hypothetical Wellfield (thicker area of the FWL)	Manatharai Wellfield	Saraapiddy Wellfield
Initial concentrations	423	5,553	2,181
Scenario A	2,756	7,810	4,813
Scenario B	1,091	5,436	3,146
Scenario C	2,018	6,580	4,323
Scenario D	460	5,615	2,362

The limitations of the model due to its simplification must be reiterated. VES surveys confirmed a heterogeneous aquifer and irregularly shaped FWL. Moreover, a recharge assessment of the area conducted parallel to this study by Wu (2020) reflected an unevenly distributed recharge in areas of the island; recharge also occurs mainly during the wet season. Uncertainty further exists around the volume of water abstracted and pumping rates at wells to meet the demands of residents due to the lack of a monitoring system. Thus, the extent of the FWL and the absolute values of this model serves to understand the sensitivity of parameters. The model is also useful for displaying the impacts of abstractions from point sources and distributed methods, on the FWL. The results can assist in simple management decisions towards developing sustainability in water resources.

FWL reduction, increasing the volume of the transition zones, and upconing are usually the results of abstraction from a thin FWL (Volker *et al*., 1985; Werner *et al*., 2017) and particularly so for vertical wells. The threat is exacerbated by coastal retreat resulting from rising sea-levels (Oude Essink, 2001). With Delft Island's growing permanent (returning residents) and transient (tourists) population, there is a need for either a change in the method of groundwater abstraction or controlling abstractions to preserve the FWL. This is particularly so for the Manatharai wellfield, which faces natural threats of overwash due to storm surges and has higher TDS concentrations in wells. Controlling abstractions can preserve the water salinity or act as a buffer zone to the lateral encroachment of saline waters.

Radial skimming wells are known to be particularly useful in areas with FWL thinner than 5 m with shallow water tables and result in a limited disturbance on the underlying layer of saline water (Rao *et al*., 2006; 2007). The drawdown from skimming wells is relatively small, and on Tarawa Atoll (Kiribati) it was found that the drawdown was less than the diurnal tidal variation (White *et al*., 2007). Sustainable large-scale water supply has been achieved using horizontal abstraction systems (skimming wells and abstraction galleries) (Falkland, 2000b) and has become widespread in

Tarawa and Kiritimati (Kiribati), Aitutaki Island (Cook Islands) and Majuro and Kwajalein Atolls (Marshall Islands) (Hunt & Peterson, 1980; Peterson, 2004; White & Falkland, 2009). An infiltration gallery is a permeable, horizontal or inclined conduit into which water infiltrates from an overlying or adjacent source of water (Nissen-Petersen, 1997). Horizontal abstraction systems have been used on the Tarawa Atoll (Bonriki Island) as a standalone option with a desalination plant as a supplementary system for droughts (White *et al*., 2007).

The results of these scenarios combined with the uncertainties in the extent of the FWL highlight that changing the method of abstractions is only one step towards sustainability. Further assessment is needed to develop a sustainable abstraction plan and in turn a sustainable water resources management plan. Other avenues for freshwater (e.g. rainwater harvesting, desalinisation etc.) should also be developed, to avoid the further salinisation of the FWL. This is particularly vital for the dry season where water reserves are depleted and become brackish. Moreover, the already limited freshwater lens needs to be preserved from contaminating practices such as agriculture or wastewater discharge, which have been observed in the area.

05

Recommendations

Uncertainties due to climate variability and rising sea-levels bring additional pressures to the freshwater reserves on Delft Island. Combined with a growing population, the unabated exploitation of the island's aquifer will further deplete its volume and worsen its quality. Hence, the development of sustainable water resources management plan is essential in preventing the total deterioration of available fresh groundwater reserves of the island. Considerations for abstractions should include sustainable groundwater yield. Furthermore, the island should supplement freshwater demand with existing sources, like its desalination plant and explore other low-cost and/or environment-friendly options.

The lack of baseline data on water quality and quantity, particularly in the major wellfields, makes it difficult to formulate and implement sustainable water management strategies that are tailored to the aquifer conditions. Systematic monitoring of groundwater level fluctuations in the wells in response to rainfall events (and possibly tidal actions) should be done, along with the regulation of water use and demand. Groundwater level monitoring can be achieved using inexpensive means and minimal training (Calderwood *et al*., 2020). Furthermore, since the transition zone is indicative of the recharge process, piezometers should be installed at different depths to include the transition zone (Falkland & Custodio, 1991).

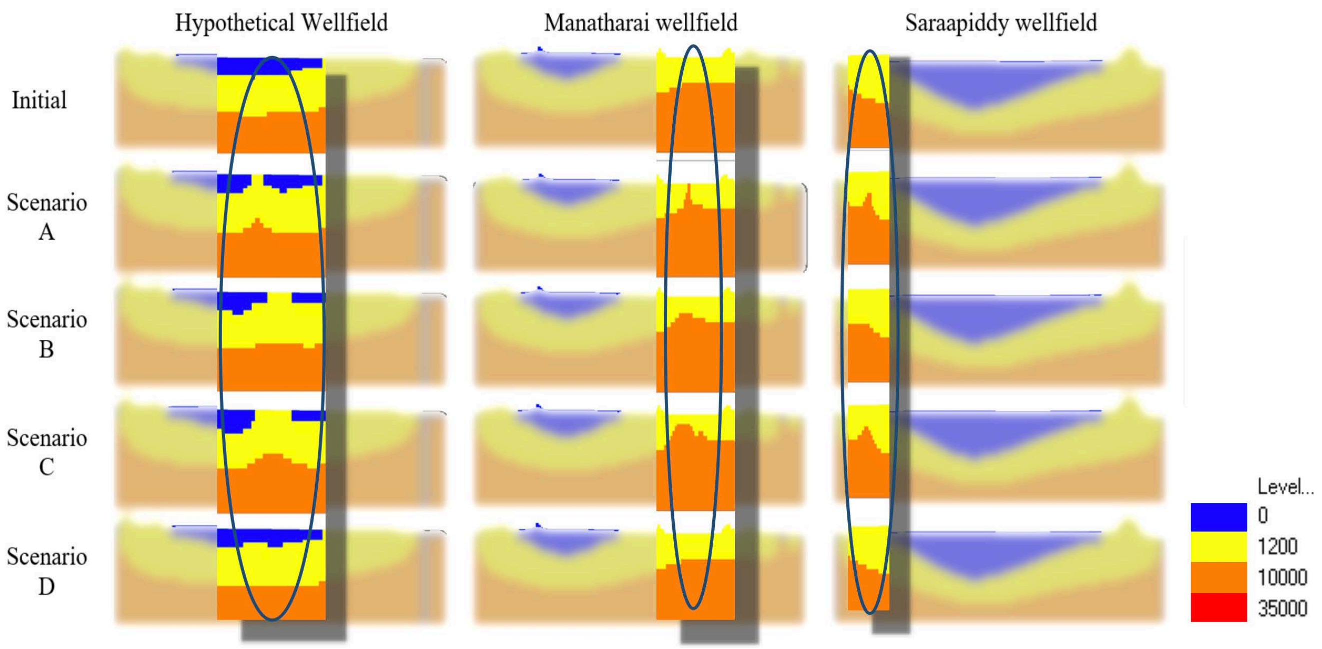


Figure 7-12 *Cross-sections of the freshwater lens (from West to East), showing IDS concentrations for the Scenario listed in Table 7-4. Encircled areas highlight the locations of the wellfields in the cross-section*

Groundwater quality needs to be carefully monitored, thereby mitigating and preventing nitrate contamination to preserve the already limited freshwater lens. The spatiotemporal variations can be linked to agricultural practices and wastewater discharge. Monitoring should include tests for microbiological contamination to detect a possible correlation to high nutrient levels and determine the sources of contamination (Chapelle, 2000).

Moreover, understanding the consumption patterns of groundwater reserves can improve water resource management. The regulation of groundwater abstractions require the participation of all stakeholders and necessitates intensive cooperation between the local government and water users. Regular meetings, seminars, and training programs should be open for social learning through the exchange of ideas and perspectives between the water users and authorities. The importance of sustainable and responsible water use should be reiterated in the educational system.

Technical measures should be considered to increase water supply and prevent or control saltwater intrusion, but these can be costly. These measures can be used in conjunction with horizontal abstractions and may include: rainwater harvesting methods (Bailey *et al*., 2018); seawater and physical barriers (Sugio *et al*., 1987; Falkland & Custodio, 1991; Banerjee & Singh, 2011; Hussain *et al*., 2019) and hydraulic barriers (freshwater injection wells and seawater pumping wells) (Hussain *et al*., 2019). Note that hydraulic barriers require studies to improve understanding of the aquifer characteristics to mitigate the impacts on dependent coastal ecosystems.

Increasing the recharge and reducing saltwater intrusion can also be accomplished using managed aquifer recharge (MAR). There are merits in MAR techniques, but they are not prevalent in atoll islands. An exception is found in the Roi-Namur atoll study in which MAR was coupled with vegetation alteration resulting in a significant increase in the water supply (Hejazian *et al*., 2017). On Delft Island, freshwater from inundated areas can be injected or diverted (via drains) to areas of higher recharge during the wet season, and the seawater that is pumped out can be processed in the reverse osmosis plant situated on the island. This approach can provide a multi-purpose solution to excessive inundation of areas during the wet season.

Overall, technical and financial support, as well as coordination among various government and non-government units, are necessary to implement these measures due to the high demand for financial resources and expertise. Additionally, the impacts on the environment (fishing resources and other ecosystem services) would need to be assessed before any action is taken (Hussain *et al*., 2019).

06

Conclusion

In Delft Island, Sri Lanka, the scarcity of reliable freshwater is a current problem and is also expected to impede further socio-economic development. The lack of understanding of the spatial distribution of the island's freshwater lens hinders the formulation of a sustainable water management plan. Geophysical and hydrochemical assessments were conducted to evaluate the spatial distribution of the fresh and saline waters on the island and ascertain the major processes controlling the groundwater salinity. Numerical modelling was used to assess the FWL sensitivity to recharge and hydraulic parameters and infer the potential for abstraction.

Correlation of VES surveys and well observations revealed the occurrence of a thin irregularly-shaped FWL with a maximum thickness of 3.3 m in the Saraapiddy area, and overall the shallow occurrence of saline water within the island, mainly as a consequence of the high transmissivity of the coral limestone. High salinity levels were mostly caused by mixing with seawater, although surface water also revealed significant evapoconcentration. The combination of high alkalinity and salinity in some wells revealed the percolation of saline water through the root zone, probably originating from overwash linked to tropical cyclones, although the capillary rise of saline water cannot be excluded.
High nutrient levels found in groundwater may impair the use of the freshwater lens for drinking water, as well as endangering groundwater-dependent ecosystems in groundwater discharge zones.

A simplified model of the island revealed that the FWL and transition zone thickness are sensitive to recharge, hydraulic conductivity and mechanical dispersion factors. Moreover, the model showed that point abstractions result in upconing in wells, hence abstraction potential is low for long term abstractions using this method. In contrast, changing the method of abstraction to horizontal or skimming wells can reduce the rates of upconing for similar yields.
However, distributed abstractions should be done moderately and from the thicker parts of the freshwater lens, possibly in combination with MAR, since lateral saltwater intrusion becomes a threat in coastal areas when abstracting from thinner areas of the FWL.

References

Abdullah, M. H., Raveena, S. M. & Aris, A. Z. (2010). A Numerical Modelling of Seawater Intrusion into an Oceanic Island Aquifer, Sipadan Island, Malaysia. *Sains Malaysiana*, 39(4), pp. 525–532.

APHA (American Public Health Association). (2005). Standard methods for the examination of water and wastewater, 21st edn. American Public Health Association, New York.

Appelo, C. A. J. & Postma, D. (2005). Geochemistry, groundwater and pollution, 2nd Edition. A.A. Balkema Publishers, Rotterdam, The Netherlands. DOI:http://dx.doi.org/10.1201/9781439833544.

Aris, A. Z., Abdullah, M. H., Ahmed, A. & Woong, K. K. (2007). Controlling factors of groundwater hydrochemistry in a small island's aquifer. *International Journal of Environmental Science & Technology*, 4, pp. 441-450. https://doi.org/10.1007/BF03325979.

ASTM (American Society for Testing and Materials). (1982). Standard Methods for Acidity or Alkalinity of Water. Publ. D1067-70 (reapproved 1977), American Soc. Testing & Materials, Philadelphia, Pa.

Bailey, R. T. & Kivi, S.T. (2017). Method for estimating available groundwater volume of small coral islands. *Hydrological Sciences Journal*, 62:14, pp. 2381-2392. DOI: 10.1080/02626667.2017.1382703.

Bailey, R. T., Beikmann, A., Kottermair, M., Taboroši, D. & Jenson, J. W. (2018). Sustainability of rainwater catchment systems for small island communities. *Journal of Hydrology*, 557. https://doi.org/10.1016/j.jhydrol.2017.12.016.

Banerjee, P. & Singh, V. S. (2011). Optimization of pumping rate and recharge through numerical modelling with special reference to small coral island aquifer. *Physics and Chemistry of the Earth, Parts A/B/C*, 36(16), pp. 1363-1372. DOI:https://doi.org/10.1016/j.pce.2011.04.014.

Barnett, J. & Adger, W. N. (2003). Climate dangers and atoll countries. *Climatic Change*, 61, pp. 321–337. DOI:10.1023/B:CLIM.0000004559.08755.88.

Bhattacharya, P. K. & Patra, H. P. (1968). Direct current geoelectric sounding: principles and interpretation. Amsterdam; London: Elsevier.

Bhoyar, M. (2015). Modern techniques for salt stress management in fruit crops.

Bryan, E., Meredith, K. T., Baker, A., Andersen, M. S. & Post, V. E. A. (2017). Carbon dynamics in a Late Quaternary-age coastal limestone aquifer system undergoing saltwater intrusion. *Science of the Total Environment*, 607–608, pp 771-785. ISSN 0048-9697.

Burkepile, D. E., Shantz, A. A., Adam, T. C., Munsterman, K. S., Speare, K. E., Ladd, M. C., Rice, M. M., Ezzat, L., McIlroy, S., Wong, J. C. Y., Baker, D. M., Brooks, A. J., Schmitt, R. J. & Holbrook, S. J. (2020). Nitrogen Identity Drives Differential Impacts of Nutrients on Coral Bleaching and Mortality. *Ecosystems*, 23, pp. 798–811. https://doi.org/10.1007/s10021-019-00433-2.

Calderwood, A. J., Pauloo, R. A., Yoder, A. M., Fogg, G. E. (2020). Low-Cost, Open Source Wireless Sensor Network for Real-Time, Scalable Groundwater Monitoring. *Water*, 12, p. 1066. https://doi.org/10.3390/w12041066.

Calvache, M. L. & Pulido-Bosch, A. (1994). Modeling the effects of salt-water intrusion dynamics for a coastal karstified block connected to a detrital aquifer. *Groundwater*, 32(5), pp. 767-777.

Celle, H., Gonfiantini, R., Travi, Y. & Sol, B. (2004). Oxygen-18 variations of rainwater during precipitation: application of the Rayleigh model to selected rainfalls in Southern France, *Journal of Hydrology*, 289, pp. 165–177. DOI: 10.1016/j.jhydrol.2003.11.017.

Chapelle, F. H. (2000). Ground-water microbiology and geochemistry: New York, John Wiley and Sons, p. 468.

Craig, S. G. (2020). Field assessment and numerical modelling of groundwater storage and abstraction potential on a semi-arid coral island. Delft Island, Sri Lanka [unpublished MSc thesis]. MSc Thesis, IHE Delft Institute for Water Education.

Dose, E. J., Stöckl, L., Houben, G., Vacher, L. H., Vassolo, S., Dietrich, J. & Himmelsbach, T. (2014). Experiments and modeling of freshwater lenses in layered aquifers: Steady state interface geometry. *Journal of Hydrology*, 509, pp. 621–630. DOI: 10.1016/j.jhydrol.2013.10.010.

Duncan, D. (2012). Freshwater Under Threat: Pacific Islands. Vulnerability Assessment of Freshwater Resources to Environmental Change. United Nations Environment Programme (UNEP). ISBN: 978-92-807-3132-3.

Falkland, A. (2000b). An outline of recent water supp improvements for Pangai-Hihifo, Lifuka, Kingdom of Tonga. Prepared for Tongo Water Board, August 2000.

Falkland, A. & Custodio, E. (1991). Hydrology and water resources of small islands: a practical guide. International Hydrological Programme, IHP-111, Project 4.6. United Nations Educational, Scientific and Cultural Organization 7. Place de Fontenoy, 75700 Paris.

Falkland, A. C. (1994a). Climate, Hydrology and Water Resources of the Cocos (Keeling) Islands: Atoll Research Bulletin No. 400. Smithsonian Institute, Washington, D.C. p. 23.

______. (2002b). Tropical island hydrology and water resources current knowledge and future needs. In Gladwell, J. S. (ed.) Hydrology and water resources management in the humid tropics, Proceedings of the second

International Colloquium, 22nd–26th March 1999, Panama, Republic of Panama, IHP-V Technical Documents in Hydrology No 52, UNESCO, Paris, 2002, pp. 237-285.

Galloway, J. N., Townsend, A. R., Erisman, J. W., Bekunda, M., Cai, Z., Freney, J. R., Martinelli, L. A., Seitzinger, S. P. & Sutton, M. A. (2008). Transformation of the N cycle: recent trends, questions and potential solutions. *Science*, 320, pp. 889-892.

Ghyben, W. (1889). Nota in verband met de voorgenomen put boring rtabij Amsterdam. K Inst Ingen Tijdschr Hague 1888–89:8–22.

Goonatilake, Sd. A., Ekanayake, S., Kumara, T. P., Liyanapathirana, D., Weerakoon, D. K. & Wadugodapitiya, A. (2013). Sustainable development of Delft Island: An ecological, socio-economic and archaeological assessment. Occasional Papers of IUCN Sri Lanka. No. 014. Colombo. IUCN. ISBN 978-955-0205-18-9.

Guo, W. & Langevin, C. D. (2002). User's guide to SEAWAT; a computer program for simulation of three-dimensional variable-density ground-water flow.

Han, D. M., Song, X. F., Currell, M. J., Yang, J. L. & Xiao, G. Q. (2014). Chemical and isotopic constraints on evolution of groundwater salinization in the coastal plain aquifer of Laizhou Bay, China. *Journal of Hydrology*, 508, pp. 12–27. DOI: http://dx.doi.org/10.1016/j.jhydrol.2013.10.040.

Harbaugh, A. W., Banta, E., Hill, M. & McDonald, M. G. (2000). MODFLOW-2000, the U.S. geological survey modular ground-water flow model-User guide to modularization concepts and the ground-water flow process. U.S. Geological Survey Open-File Report 00-92.

Hejazian, M., Gurdak, J. J., Swarzenski, P., Odigie, K. O. & Storlazzi, C. D. (2017). Land-use change and managed aquifer recharge effects on the hydrogeochemistry of two contrasting atoll island aquifers, Roi-Namur Island, Republic of the Marshall Islands. *Applied Geochemistry*, 80, pp. 58-71.

Herzberg, B. (1901). Die Wasserversorgung einiger Nordseebader. *J Gasbeleuchtung und Wasserversorgung Munich Jahrg*, 44, pp. 815–819.

Hiscock, K. M. & Bense, V. F. (2014) Hydrogeology: Principles and Practice, 2nd edition. Wiley Blackwell.

Holding, S., Allen, D. M., Foster, S., Hsieh, A., Larocque, I., Klassen, J. & Van Pelt, S. C. (2016). Groundwater vulnerability on small islands. *Nature Climate Change*, 6(12), pp. 1100-1103. DOI:10.1038/nclimate3128.

Hunt, C. D., Peterson, F. L. (1980). Groundwater resources of Kwajalein Island, Marshall Islands. Technical Report No.126, Water Resources Research Center, University of Hawaii, p. 91.

Hussain, M. S., Abd-Elhamid, H. F., Javadi, A. A. & Sherif, M. M. (2019). Management of Seawater Intrusion in Coastal Aquifers: A Review. *Water*, 11(12), p. 2467. MDPI AG. Retrieved from http://dx.doi.org/10.3390/w11122467.

IAEA. (n.d.). Sampling Procedures for Isotope Hydrology. International Atomic Energy Agency, Water Resources Program.

IAEA/WMO. (2020). Global Network of Isotopes in Precipitation. The GNIP Database. Accessed from https://nucleus.iaea.org/wiser.

Jayasingha, P., Pitawala, A. & Dharmagunawardhane, H. A. (2012). A Review on Nutrient Pollution of Coastal Aquifers of Sri Lanka. V. Subramanian (ed.) *Coastal Environments: Focus on Asian Coastal Regions*. DOI: 10.1007/978-90-481-3002-3_5.

Jeyaruba T. & Thushyanthy M. (2009). The effect of agriculture on quality of groundwater: A case study. *Middle-East Journal of Scientific Research*, 4(2), pp. 110–114.

Johnson, K. S. & Petty, R. L. (1983). Determination of nitrate and nitrite in seawater by flow injection analysis. DOI: https://doi.org/10.4319/l/Lo.1983.28.6.1260.

Kench, P., McLean, R. F., Brander, R. W., Nichol, S. L., Smithers, S. G., Ford, M. R., Parnell, K. E. & Aslam, M. (2006). Geological effects of tsunami on midocean atoll islands: the Maldives before and after the Sumatran tsunami. *Geology*, 34 (3), pp. 177–180. DOI:10.1130/G21907.1.

Langevin, C. D. & Guo, W. (2006). MODFLOW/MT3DMS-Based Simulation of Variable-Density Ground Water Flow and Transport. *Ground Water*, 44(3), pp. 339-351. DOI:10.1111/j.1745-6584.2005.00156.x.

Llangasekare, T., Tyler, S., Clement, T. P., Villholth, K., Perera, A. P., Obeysekera, J., Gunatilaka, A., Panabokke, C. R., Hyndman, D., Cunningham, K., Kaluarachchi, J., Yeh, W. W., Genuchten, M. T., Jensen, K. H. (2006). Impacts of the 2004 tsunami on groundwater resources in Sri Lanka. *Water Resources Research*. DOI: https://doi.org/10.1029/2006WR004876.

Mahagamage, Y. & Manage, P. (2019). Water quality and microbial contamination status of ground-water in Jaffna Peninsula, Sri Lanka. *Journal of Water and Land Development*, 40, pp. 3-12. DOI:10.2478/jwld-20190001.

McDonald, M. & Harbaugh, A. (1988). A Three-Dimensional Finite-Difference Ground-Water Flow Model. In (Vol. 83).

Nissen-Petersen, E. (1997). Water from sand-rivers. Loughborough University. Conference contribution. https://hdl.handle.net/2134/30586.

Oberle, F., Swarzenski, P. & Storlazzi, C. (2017). Atoll Groundwater Movement and Its Response to Climatic and Sea-Level Fluctuations. *Water*, 9, 650. DOI: 10.3390/w9090650.

OHCHR W, HABITAT O. (2010).
The Right to The Water, Fact Sheet No. 35 Geneva: Office of the United Nations High Commissioner for Human Right.

Orellana, E. & Mooney, H. M. (1966). Master tables and curves for vertical electrical sounding over layered structures.
Tablas y curvas patrón para sondeos eléctricos verticales sobre terrenos estratificados. Madrid: Interciencia.

Oude Essink, G. H. P. (2001). Improving fresh groundwater supply - problems and solutions.
Ocean & Coastal Management, 44, pp. 429–449.

Pastore, M. (2014). The Impact of Nitrogen Eutrophication on Caribbean Coral Reefs: A Review. Concept, Vol. XXXVII.

Peterson, F. (1997). Chapter 20 Hydrogeology of the Marshall Islands. Developments in Sedimentology, 54.
DOI:10.1016/S0070-4571(04)80042-6.

Peterson, F. L. (2004). Chapter 20: hydrogeology of the Marshall Islands. In Vacher, H. L., Quinn, T. M. (eds.)
Geology and Hydrogeology of Carbonate Islands, Developments.

Polemio, M. & Walraevens, K. (2019).
Recent Research Results on Groundwater Resources and Saltwater Intrusion in a Changing Environment. *Water*, 11, 1118.
DOI: 10.3390/w11061118.

Post, V. E. A., Bosserelle, A. L., Galvis, S. C., Sinclair, P. J. & Werner, A. D. (2018).
On the resilience of small-island freshwater lenses: evidence of the long-term impacts of groundwater abstraction on Bonriki Island, Kiribati. *Journal of Hydrology*, 564, pp. 133–148.
https://doi.org/10.1016/j.jhydrol.2018.06.015.

Praveena, S. M. & Aris, A. Z. (2009). A review of groundwater in islands using SWOT analysis:
World Review of Science, Technology and Sustainable Development, 6, pp. 186–203.

Presley, T. K. (2005). Effects of the 1998 drought on the freshwater lens in the Laura area, Majuro Atoll,
Republic of the Marshall Islands. Reston, Virginia: USGS, USGS Scientific Investigations Report 2005-5098.

Rao, S. V. N., Kumar, S., Shekhar, S. & Chakraborty, D. (2006).
Optimal pumping from skimming wells. *ASCE Journal of Hydrologic Engineering*, 11, 5, pp. 464-471.

Rao, S. V. N., Kumar, S., Shekhar, S. & Sinha, S. K. (2007).
Optimal operation of skimming wells – A case study in river Yamuna flood plain at Palla in north India 15:6 of
Hydrogeology Journal, pp. 1157-1167.

Ravichandran, P. (2018). Still standing: how palmyra trees withstood the force of the cyclone.
Accessed from https://www.thehindu.com/news/national/tamil-nadu/still-standing-how-palmyra-trees-withstood-the-force-of-the-cyclone/article25588754.ece.

Saxena, S., Shrivastava, J. P., Rao, M. S. & Kumar, B. (2014). *Isotopic-Chemical Framework of Groundwater Aquifer to study the Pollution Dynamics at Delhi, India*, pp. 138-153. ISBN: 978-93-81891-06-3.

Stigter, T. Y., Ribeiro L. & Carvalho Dill, A. M. M. (2006).
Evaluation of an intrinsic and a specific vulnerability assessment method in comparison with groundwater salinisation and nitrate contamination levels in two agricultural regions in the south of Portugal. *Hydrogeology Journal*, 14(1-2), pp. 79-99.
DOI:10.1007/s10040-004-0396-3.

Stofberg, S. F., Essink, G. H. P. O., Pauw, P. S., de Louw, P. G. B., Leijnse, A. & van der Zee, S. E. A. T. M. (2016).
Fresh Water Lens Persistence and Root Zone Salinization Hazard Under Temperate Climate. *Water Resour Manage*, 31, pp. 689–702.
https://doi.org/10.1007/s11269-016-1315-9.

Sugio, S., Nakada, K. & Urish, D. W. (1987).
Subsurface seawater intrusion barrier analysis. *Journal of Hydraulic Engineering*, 113(HY6), pp. 767-779.

Sutharsiny, A., Manthrithilake, H., Pathmarajah, S., Thushyanthy, M. & Vithanage, M. (2014).
Seasonal variation of nitrate-N in groundwater: A case study from Chunnakam aquifer, Jaffna Peninsula.
Ceylon Journal of Science (Physi-cal Sciences), 18, pp. 01–08.

Terry, J. P. & Falkland, A. C. (2010). Responses of atoll freshwater lenses to storm-surge overwash in the Northern Cook Islands.
Hydrogeology Journal, 18, pp. 749–759.

Todd, D. (1980). Groundwater hydrology, p. 535. New York: Jon Wiley & Sons Inc.

United Nations. (2019). The Sustainable Development Goals Report 2019.
Accessed from https://unstats.un.org/sdgs.

US EPA. (1983). Methods for Chemical Analysis of Water and Wastes. United States Environmental Protection Agency.

van der Moot, N. L. (2020). GEWin-Excel: A tool to interpret VES. G-Eau Advies en Diensten.

Vithanage, M., Mikunthan, T., Pathmarajah, S., Arasalin-Gam, S. & Manthrithilake, H. (2014).
Assessment of nitrate-N contamination in the Chunnakam aquifer system, Jaffna Peninsula, Sri Lanka. Springerplus, 3, 271.
DOI: 10.1186/ 2193-1801-3-271.

Volker, R. E., Mariño, M. A. & Rolston, D. E. (1985).
Transition Zone Width in Ground Water on Ocean Atolls. *Journal of Hydraulic Engineering*, 111(4), pp. 659-676.
DOI:10.1061/(ASCE)0733-9429(1985)111:4(659).

Weerakoon, D., Goonatilake, S., Wijewickrama, T., A, Rajasuriya., Perera, N., Kumara, T. P., G, De., Miththapala, S. & Mallawatantri, A. (2018).
The Islands and Lagoons of Northern Sri Lanka By Weerakoon *et al.,* 2018 IUCN Sri Lanka.

Werner, A. D., Bakker, M., Post, V. E. A., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., Simmons, C. T. & Barry, D. A. (2013). Seawater intrusion processes, investigation and management: Recent advances and future challenges. *Advances in Water Resources*, 51, pp. 3–26.

Werner, A. D., Sharp, H. K., Galvis, S. C., Post, V. E. A. & Sinclair, P. (2017). Hydrogeology and management of freshwater lenses on atoll islands: Review of current knowledge and research needs. *Journal of Hydrology*, 551, pp. 819-844. https://doi.org/10.1016/j.jhydrol.2017.02.047.

Whitaker, F. F. & Smart, P. L. (2004). Chapter 4: Hydrogeology of the Bahamian archipelago. In Vacher, H. L. & Quin, T. M. (eds.) *Geology and Hydrogeology of Carbonate Islands, Developments in Sedimentology 54*. Elsevier, Amsterdam, pp. 183–216. 0-444-51644-1.

White, I. & Falkland, T. (2009). Management of freshwater lenses on small Pacific islands. *Hydrogeology Journal*, 18 (1), pp. 227–246. http://dx.doi.org/10.1007/s10040-009-0525-0.

White, I., Falkland, T., Metutera, T., Metai, E., Overmars, M., Perez, P. & Dray, A. (2007). Climatic and Human Influences on Groundwater in Low Atolls. Vadose Zone Journal - VADOSE ZONE J, 6. DOI:10.2136/vzj2006.0092.

White. I., Falkland. A., Etuati, B., Metai, E. & Metutera, T. (2002). Recharge of fresh groundwater lenses: field study, Tarawa Atoll, Kiribati. Hydrology and Water Resources Management in the Humid Tropics, Proc. Second International Colloquium, 22–26 March 1999, Panama, Republic of Panama, IHP-V Technical Documents in Hydrology No 52, UNESCO, Paris, 2002, pp. 299–332.

WHO. (2011) Guidelines for Drinking-water Quality, Fourth Edition. ISBN 978 92 4 154815 1.

______. (2017). Guidelines for drinking-water quality. Vol. 4, Fourth edition Incorporating the first addendum. In (2nd ed ed.). Geneva: World Health Organization.

Wijayawardene, L., Witharanage, D. N. S. & Fahim, A. A. M. (2015). Resilience Analysis Protocol to Sustainable Development of Delft Island in Sri Lanka. x + 83 pp, IUCN Sri Lanka Country Office, Colombo. http://iucn.org/srilanka.

Wilson, A. M., Moore, W. S., Joye, S. B., Anderson, J. L. & Schutte, C. A. (2011). Storm-driven groundwater flow in a salt marsh. *Water Resources Research*, 47:W02535. https://doi.org/10.1029/2010WR009496.

Woodroffe, C. D. & Falkland, A. C. (2004). Chapter 31 - Geology and Hydrogeology of the Cocos (Keeling) Islands. In Vacher, H. L. & Quinn, T. M. (eds.) *Developments in Sedimentology*, 54, pp. 885-908. Elsevier.

Woodroffe, C. D. (2008). Reef-island topography and the vulnerability of atolls to sea-level rise. *Global and Planetary Change*, 62, pp. 77–96. DOI:10.1016/j.gloplacha.2007.11.001.

Wu, C. L. R. (2020). Investigating the occurrence and hydrochemistry of fresh-saline waters as a function of recharge and hydrogeological setting on Delft Island - A semi-arid coral reef island in Sri Lanka [unpublished MSc thesis]. MSc Thesis, IHE Delft Institute for Water Education.

Xiao, Y. & Gu, X. (2017). Investigation of Geochemical Characteristics and Controlling Processes of Groundwater in a Typical Long-Term Reclaimed Water Use Area. *Water*, 9(10), 800. DOI: 10.3390/w9100800.

Zendehbad, M., Cepuder, P., Loiskandl, W. & Stumpp, C. (2019). Source identification of nitrate contamination in the urban aquifer of Mashhad, Iran. *Journal of Hydrology: Regional Studies*, 25, 100618. ISSN: 2214-5818. DOI: https://doi.org/10.1016/j.ejrh.2019.100618.

Zheng, C. & Wang, P. (1999). MT3DMS: A Modular Three-Dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems; Documentation and User's Guide.

IV

Remediation

8

Groundwater Quality, Pollution Control, and Climate Change

Malcolm J. Gander

Malcolm J. Gander, Remedial Project Manager, Department of Defense, USA.
e-mail: malcolmgander@comcast.net

Abstract

Given that almost half of the world's drinking water is from groundwater, and groundwater extraction is increasing, groundwater protection should be promoted, and groundwater restoration to various levels of water quality should be pursued where appropriate. Where naturally-occurring or anthropogenic (man-made) pollution exists, cost-effective remediation technologies are available to restore portions of an aquifer to quality levels that may be suitable for agricultural or industrial use.
Remediation to drinking water quality levels will be more costly than for other uses, and take longer to achieve, but can likewise be attained. Usable water can be extracted within the radius of influence of a pumping well even where aquifer contamination extends beyond the well.
The study details the principal types of anthropogenic and naturally-occurring groundwater pollutants, and effective methods of groundwater remediation technologies. These conditions and processes are examined in the context of climate change.
Additionally, successful case studies are presented, which demonstrate reduction of contaminant concentrations to usable levels by promoting growth of indigenous bacteria (biostimulation) to lower contaminant concentrations as bacteria can metabolize fuels, solvents or explosives.
Whenever possible, water managers should consider existing groundwater quality from an aquifer, so lower quality water is matched with the appropriate agricultural or industrial application, and ideally save high quality groundwater for use as a drinking water source.

Keywords

Groundwater, pollution. per- and polyfluoroalkyl substances (PFAS), climate change, remediation, bioremediation

01

Types of Groundwater Pollution

Groundwater pollution can be grouped into two categories: naturally-occurring and anthropogenic pollution. An example of natural pollution is the high concentrations of arsenic (As) in Bangladesh groundwater, which is generally believed to originate from the unconsolidated sediments (sands, silts, clays and gravels) that host the groundwater.

Most anthropogenic groundwater pollution can be categorized into either agricultural, sewage, or industrial pollution (Figure 8-1). There is widespread nitrate and phosphate pollution from agricultural and sewage sources, including fertilizers, animal manure and human sewage, and detergents.

Industrial pollutants can be grouped as fuels (gasoline, diesel), solvents (degreasers including trichloroethylene), metals (cars, batteries), semi-volatile organic compounds (pesticides, polychlorinated biphenyls [PCBs]), and wood treatment compounds (pentachlorophenol in creosote); explosives, and per- or polyfluoroalkyl substances (PFAS) in Teflon, Gore-Tex, aqueous fire fighting foam [AFFF], also known as aqueous film forming foam, and metal plating baths. PFAS are a widespread emerging class of compounds whose toxicity is still being defined.

The effects of climate change on the transport, fate and remediation of polluted groundwater are discussed in Section 5.

The relationship between surface water and groundwater is of fundamental importance when considering the movement of pollutants.

In many environments, surface water seeps through soil and becomes groundwater. It is also common for groundwater to feed surface water sources. Common naturally-occurring and anthropogenic groundwater pollution sources are summarized in Table 8-1.

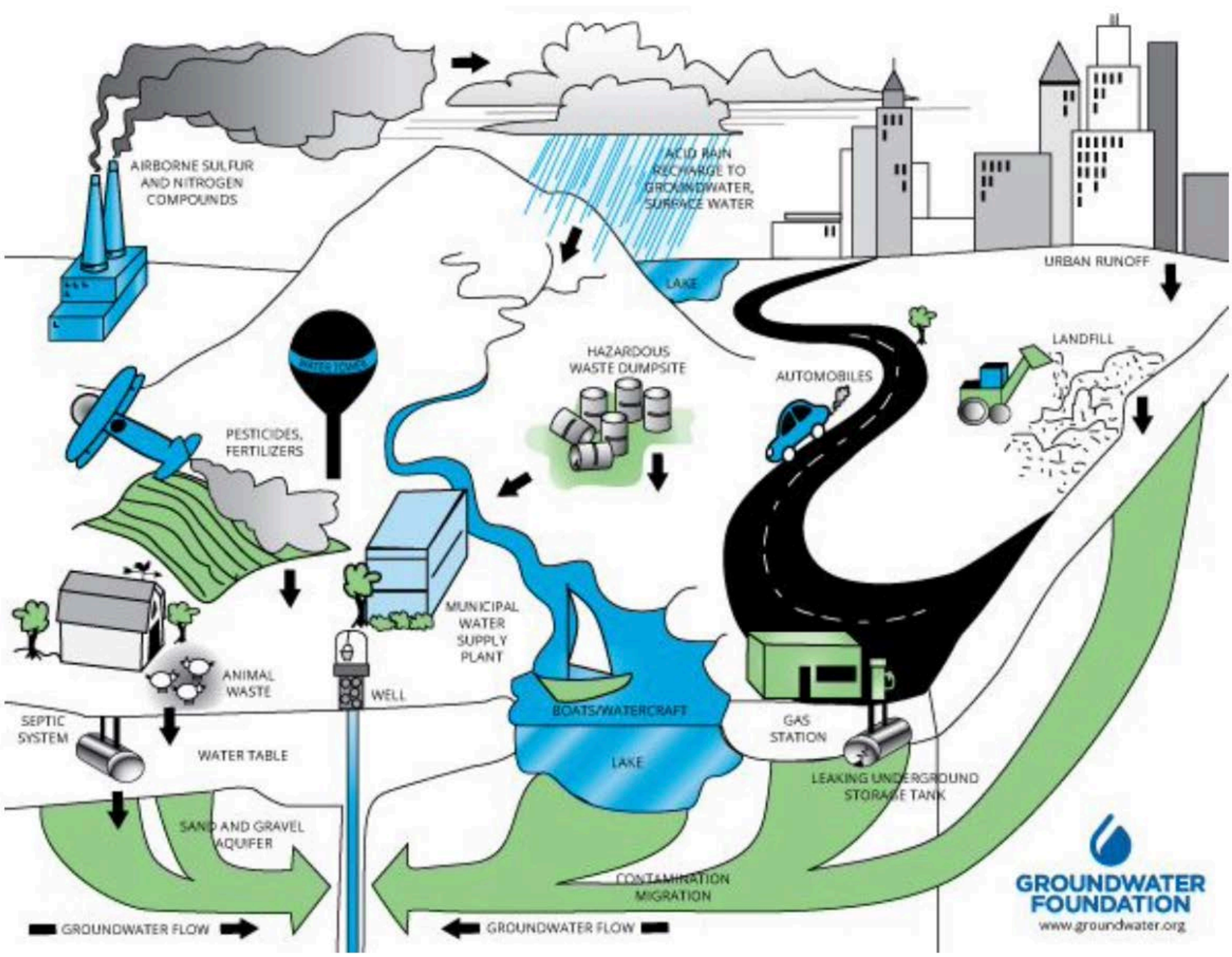


Figure 8-1 Agricultural, sewage, industrial, and other miscellaneous man-made pollution sources in air, surface water, soil and groundwater (Groundwater Foundation, 2020)

Table 8-1 Common naturally-occurring and anthropogenic groundwater pollution sources

Naturally-Occurring Groundwater Pollutants		
Type	**Source**	**Comment**
Arsenic	Soils or bedrock	Elevated arsenic may occur in many geologic environments.
Copper, Lead, Zinc, Cadmium	Higher concentrations in bedrock versus soil	Bedrock source areas may leach to groundwater
Uranium and other radionuclides	Soil or bedrock, both igneous and sedimentary rock	Elevated uranium is widespread in many aquifers in India.
Iron and Manganese	Soil or bedrock	Often found together in groundwater in elevated concentrations
Selenium	Associated with coal-bearing or volcanic rocks and soils	Selenium is a significant pollutant that is released via metal and coal mining, power plant effluent

Anthropogenic Groundwater Pollutants		
Type	**Source**	**Comment**
Fuels	Gasoline and diesel fueling stations, large spill locations	Gasoline: carcinogenic with benzene, toluene ethylbenzene
Solvents	Degreasers, cleaning solutions, pesticides, glues, resins	Perchloroethylene dry cleaning fluid formerly caused enormous groundwater pollution.
Arsenic	Mining and industrial air and water effluent; diesel exhaust	Occurs as arsenites and arsenates; carcinogenic
Heavy Metals:Copper, Lead, Zinc, Cadmium	Mining operations, industrial effluent, road runoff, open burning	These heavy metals commonly occur together.
Selenium	Metal and coal mining, effluent from power plants	Increasingly recognized as a significant pollutant that occurs naturally but is mobilized during mining.
Uranium and other radionuclides	Nuclear weapons production, nuclear power plants, coal and phosphate mining, uranium mining	Uranium, radon and radium occur together in groundwater
Nitrates, phosphates and potassium	Fertilizer runoff from agriculture, commercial or residential sources; septic systems.	Nitrates in urea or ammonium nitrate are most widely used in fertilizers
Polychlorinated Biphenyls (PCBs)	Formerly used as a di-electric oily fluid in transformers, and a lubricant.	Very stable and present throughout food chain; Banned in USA and EU
Per- and Polyfluoroalkyl substances (PFAS)	Flame-retardant in carpet, furniture; formerly in Teflon; still used in aqueous fire fighting foam (AFFF)	Over 4,000 known PFAS compounds; exceedingly stable; incompletely studied
Pentachlorophenol	Creosote, a wood preservative	Very stable compound
Prescription Drugs	Septic systems and wastewater treatment plants (WWTP)	Drugs such as antibiotics and blood-pressure medicines are being increasingly detected in groundwater
Microplastics	Plastic bags and containers	Presence and extent in groundwater is poorly known due to lack of sampling
Pesticides and Herbicides	Surficial soils in agricultural areas	Chemicals reach groundwater via runoff and leaching.

02

Groundwater Remediation: Existing and Emerging Technologies

Groundwater remediation methods can generally be grouped into three categories: containment, removal, or treatment (Water Encyclopedia, 2020).

Containment. This involves containing the contaminants to prevent them from migrating from their source.

Removal. The principal method of groundwater remediation of industrial pollutants is extraction via pumping from groundwater wells and treatment by activated carbon; or a combination of ion exchange, reverse osmosis, and/or distillation. However, it often must be operated for twenty years or more with decreasing effectiveness as the recovered contaminant mass steadily decreases. Annual operating costs remain constant and can typically range from $300,000-$500,000 USD, depending on the size of the contaminant plume (EPA, 2001, Gander, 2020) (Figure 8-2).

Treatment. This technology is applied in cases where the aquifer characteristics are complex and/or multiple contaminants exist, and it involves treating the water at its point of use. The most common forms of treatment are reverse osmosis, ion exchange, or distillation. Reverse osmosis is a water purification process that uses a partially permeable membrane to remove unwanted molecules from drinking water, and is often a pre-treatment phase followed by ion exchange. Ion exchange is a purification process using a polymeric resin such as spherical beads to capture ionic species. Distillation removes dissolved solids, some bacteria, and inorganics such as nitrates by boiling water and the vapor is collected into a container.

Bioremediation is a form of treatment where naturally-occurring microorganisms metabolize (break down) many contaminants and are being increasingly used as a remediation method. In some cases, bacteria are introduced (bioaugmentation) into groundwater after small-scale pilot testing establishes their ability to thrive and break down contaminants in a specific environment. Bacteria are provided a carbon substrate (e.g., fructose), and this biostimulation can enable achievement of clean up levels (CULs) within the radius of influence of the biostimulation within several years. Groundwater remediation technologies are summarized in Table 8-2.

PFAS compounds are unusual in that they are generally not amenable to microbial degradation. Some PFAS can be treated with activated carbon, whereas others are amenable to ion exchange. Enormous monetary resources are currently being devoted internationally to developing PFAS treatment technologies,

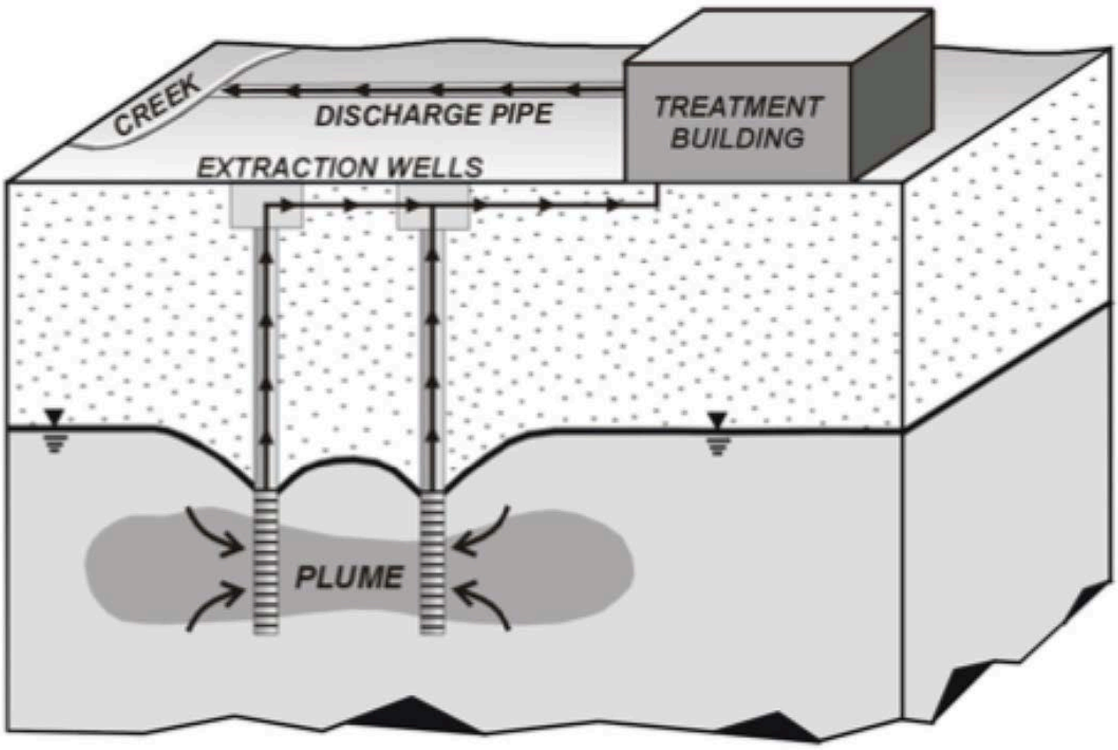


Figure 8-2 *Typical pump and treat system where contaminated groundwater is extracted; pumped through carbon; and clean water is discharged (EPA, 2001)*

Table 8-2 *Overview of groundwater remediation technologies, including technologies under development*

Principal Groundwater Remediation Technologies		
Technology	**Contaminant**	**Comment**
Pump & treat (P&T), primarily with activated carbon	Fuels, solvents, creosote (pentachlorophenol), PFAS, explosives (e.g., TNT), PCBs	P&T systems are reliable methods of groundwater treatment but routinely become less efficient as concentrations decrease over time.
Bioremediation	Fuels, solvents, creosote (pentachlorophenol), explosives (e.g., TNT), nitrates and radionuclides (e.g., uranium), metals	Microbes metabolize fuels, solvents, explosives, nitrates. In pilot tests, microbes liberate phosphate that can immobilize (sequester) uranium and metals.
pH adjustment, chemical treatment	Arsenic (a metalloid)	Immobilization by: a) pH adjustment via hydrated lime addition to inhibit oxidation of arsenical pyrite; or b) maintenance of oxidizing conditions where pyrite is absent but high As is present and immobile under oxidizing conditions.
Ion exchange, reverse osmosis, and/or distillation	Metals: Copper, Lead, Zinc, Cadmium; PFAS; Selenium	These techniques can achieve drinking water quality conditions.
Supercritical water oxidation	PFAS	Pilot testing successful to <10 parts per trillion (below health advisory)

2.1. Emerging remediation technologies

Supercritical Water Oxidation. This technology has been highly effective in small-scale laboratory pilot tests (Rosansky, 2020) in the destruction of PFAS compounds. Testing to date has achieved PFAS concentrations to five ppt (initial concentrations ~100-500 ppt) while processing 100 ml/minute, or 144 l/day (38 gallons/day). An expanded pilot test of 379 l/day (100 gallons/day) is planned for a PFAS contaminated site in Fall 2020.

Supercritical water involves subjecting water to very high temperatures and pressures where the gas and liquid phases become indistinguishable. Under these conditions, oxidation is greatly enhanced to the point where the recalcitrant chlorine-fluorine bond in PFAS compounds is broken, enabling dissociation of the compound.

Phosphate-Mediated Remediation of Metals and Radionuclides. The metals lead, zinc and cadmium, and radionuclides such as uranium, are common groundwater pollutants from miscellaneous industrial activities, and nuclear weapons production plus coal and phosphate mining, respectively. Through laboratory and field experiments, the introduction of various phosphate compounds can readily precipitate in situ insoluble metal- and radionuclide-phosphate minerals that immobilize these contaminants over a wide pH range (Martinez *et al*., 2014). Additionally, certain microorganisms' life-sustaining requirement for phosphorus serves as a mechanism to consume metals and radionuclides within polyphosphate compounds and store them within the cell structure.

This holds promise for large-scale bioremediation as the biological sequestration of contaminants is possible as long as the groundwater pH and oxidation-reduction potential is controlled. Separately, small-scale, laboratory-based studies have verified microbial mineralization (destruction) of heavy metals including cadmium and copper, and radionuclides including uranium and strontium (Martinez *et al*., 2014, Gadd, 2007). Mineralization of metals and radionuclides is ideal because the contaminant mass is destroyed and control of pH and oxidation-reduction potential is unnecessary.

03
Case Studies

Two case studies are presented that detail the use of microorganisms (bioremediation) to reduce explosives and chlorinated solvent contaminant concentrations to levels suitable for either agricultural or industrial use, or for drinking water. A third case study of two large agricultural basins is summarized, where nitrate concentrations in groundwater are being reduced through pumping the contaminated groundwater, efficient addition of fertilizer and manure to the recovered groundwater, and land application of the amended groundwater.

3.1. Explosives in Groundwater

Explosives compounds contamination in groundwater is very poorly known and assumed present in many areas in Cambodia, Laos, Vietnam, North Korea, South Korea, Afghanistan, Yemen, Iraq, Angola and Chechnya. Activities regarding explosives has almost exclusively directed funding toward the removal of unexploded ordnance, which remains a severe health hazard. Approximately twenty percent of the land area of Cambodia, Laos and Vietnam have unexploded ordnance (Martin *et al*., 2019).

The United States, Canada and Germany have by far conducted the most applied research and development concerning groundwater remediation of explosives, as the United States and Canada have over 50 million acres of contaminated lands from training and testing (Pichtel, 2012), and Germany has legacy contamination for World War II activities.

The most common explosives compounds are 1,3,5-hexahydro-1,3,5-trinitro toluene (RDX) and trinitrotoluene (TNT).

3.1.1. Pump & Treat with Bioremediation, Umatilla Chemical Depot, Umatilla, Oregon, USA

Summary Statement: At the Umatilla Chemical Depot (UMCD), bioremediation of explosives in groundwater by indigenous anaerobic bacteria achieved concentrations of 0.5 - 10 ug/L in 3-5 years in a portion of a larger 800 meter groundwater plume, using a drinking water clean-up level of 2.1 ug/L as a benchmark. This remediated water could be extracted at a rate of ~ 76 liters per minute (lpm) (20 gallons per minute) in multiple wells and used for industrial applications such as a closed-loop cooling system or open evaporative cooling system that polishes effluent with carbon to capture residual explosives.

3.1.2. Background

The UMCD (Figure 8-3) operated from 1941 until 2011, and activities included ordnance storage and destruction of chemical agents and munitions. Chemical agents were typically incinerated and conventional munitions were subjected to a steam melt-out and rinsing process. The wastewater from rinsing formed the washout lagoon and explosives compounds leached to groundwater, about 60-70 feet below ground surface. RDX and TNT are the most prevalent contaminants, with subordinate amounts of trinitrobenzene (TNB), dinitrobenzene (DNB), 2,4-dinitrotoluene (2,4-DNT), 2,6-dinitrotoluene (2,6-DNT), and octahydro-1,3,4,7-tetranitro-1,3,5,7-tetrazocine (HMX).

A pump and treat (P&T) groundwater treatment system was installed in 1997 and continues to operate. Due to the extremely long (>50 years) remediation timeframe anticipated to achieve the cleanup level, a bioremediation program was initiated in 2010 in order to more aggressively remove contaminant mass and reduce the remediation timeframe. The centerpiece of the bioremediation effort is the periodic injection of fructose corn syrup mixed with UMCD formation water, termed biostimulation.

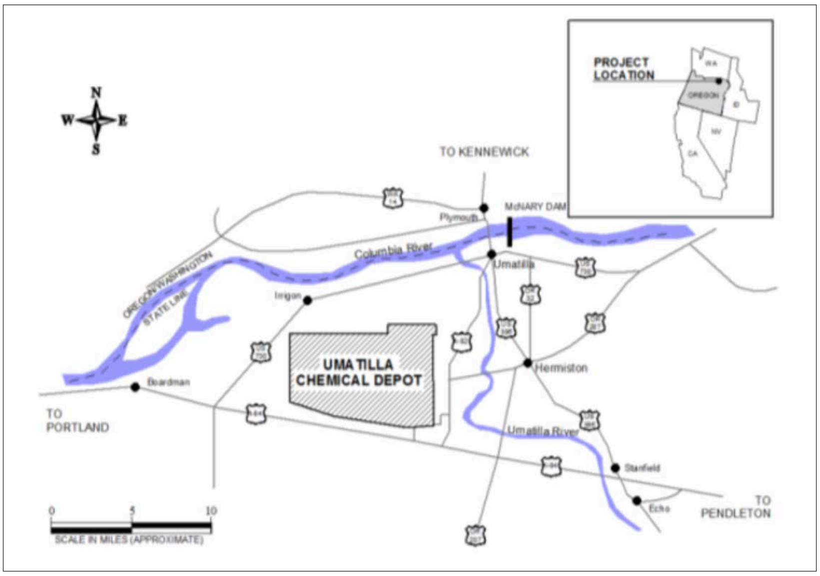


Figure 8-3 *Location of Umatilla Chemical Depot, Umatilla, Oregon, USA (USACE, 2015)*

3.1.3. Bioremediation Implementation

Figure 8-4 is a plan view of the RDX groundwater contaminant plume, which presents the progressive decrease of RDX concentrations by depicting relative concentrations before, during and after biostimulation. The highest concentrations are centered at the former washout lagoon area coincident with well 4-111.

Figure 8-5 is a cross-sectional view showing the explosives disposal lagoon in the center. Favorable bioremediation results were achieved in the vicinity of well 4-111 (near the source area), and peripheral wells WO-21 and WO-24; these three wells were used for injection of nutrients for bacteria. For these wells, the explosives (RDX) concentration was reduced to a range of <2.1 - 10 ug/L in three to five years following biostimulation using fructose.

The injection wells could be converted to pumping wells and bioremediated water could be pumped at a rate of 80 liters per minute in each well. The radius of influence of 15 meters surrounding a pumping well is a conservative

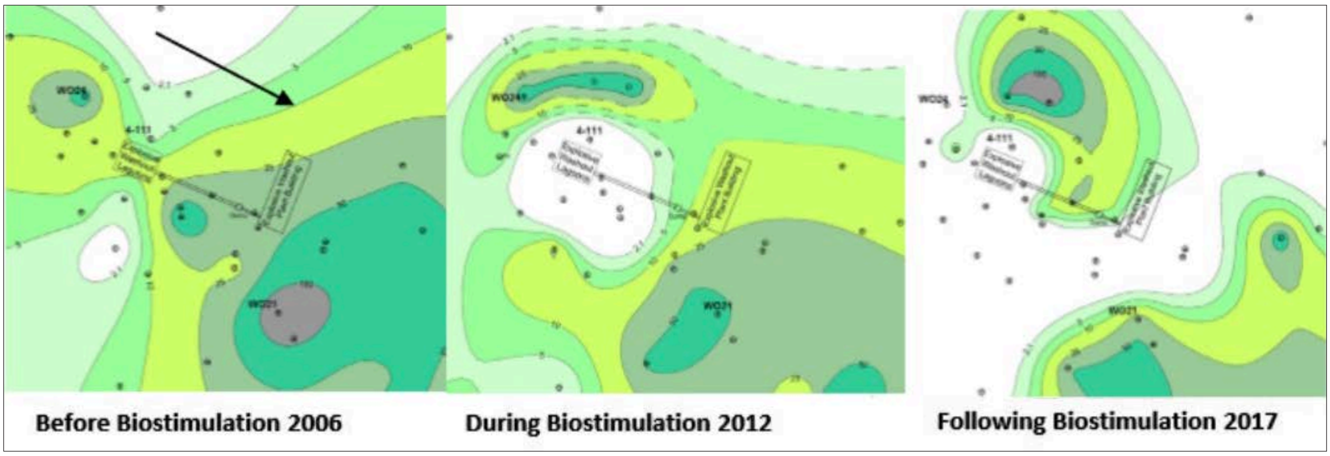


Figure 8-4 *RDX concentrations in the former washout lagoon source area before, during and after bioremediation. Purple is >100 ug/L; dark green is 50-100 ug/L; gray is 25-50 ug/L; yellow-green is 10-25 ug/L; green is 5-10 ug/L; and light green is 0-5 ug/L (Michalsen et al., 2021)*

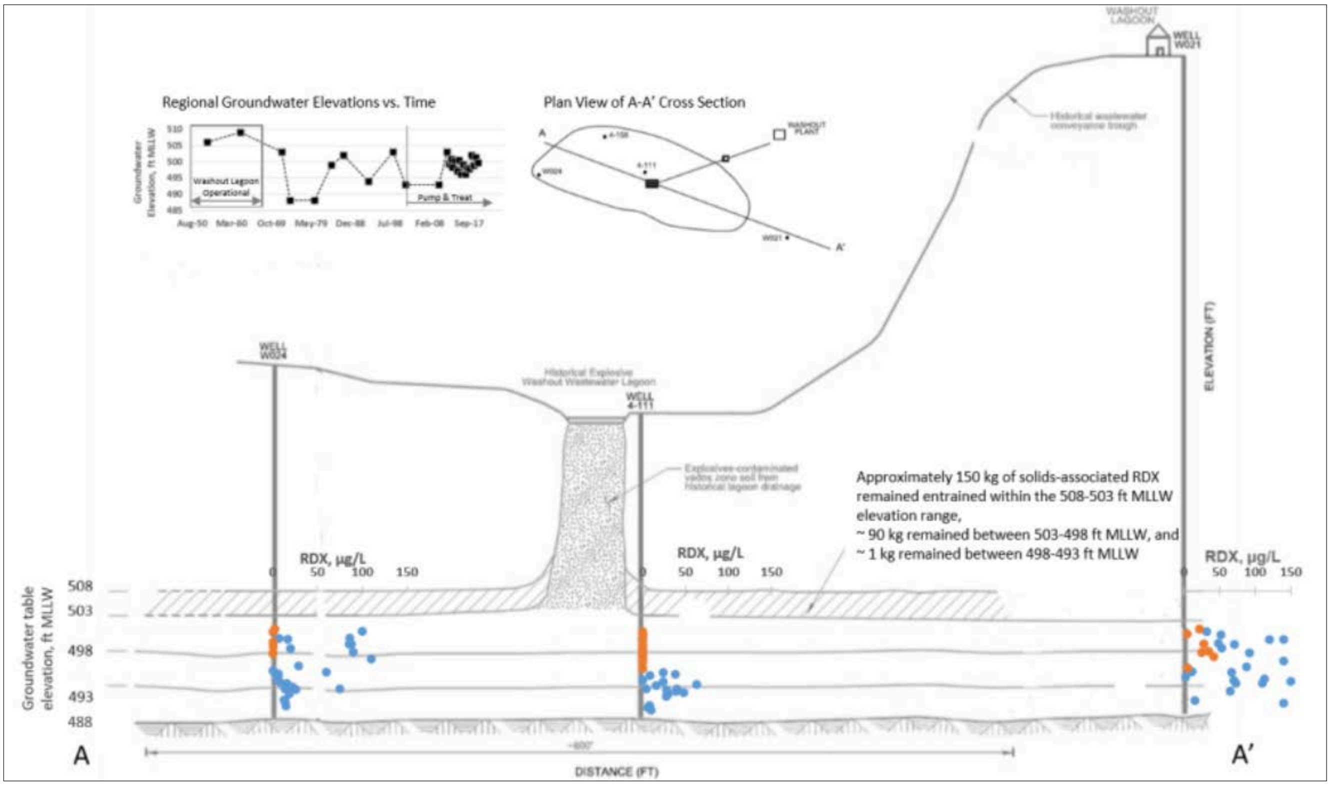


Figure 8-5 *Cross-sectional view showing the explosives disposal lagoon in the center and RDX-bearing wastewater source area to right. RDX concentrations in site wells before and after biostimulation (blue and orange circles, respectively) vs. groundwater elevation illustrate that bioremediation is capable of: a) achieving cleanup levels; and b) sustaining treatment benefit for years. Each dot is representative of the sample depth within the well, and each dot also indicates RDX concentrations from discrete samples over time (Michalsen et al., 2021)*

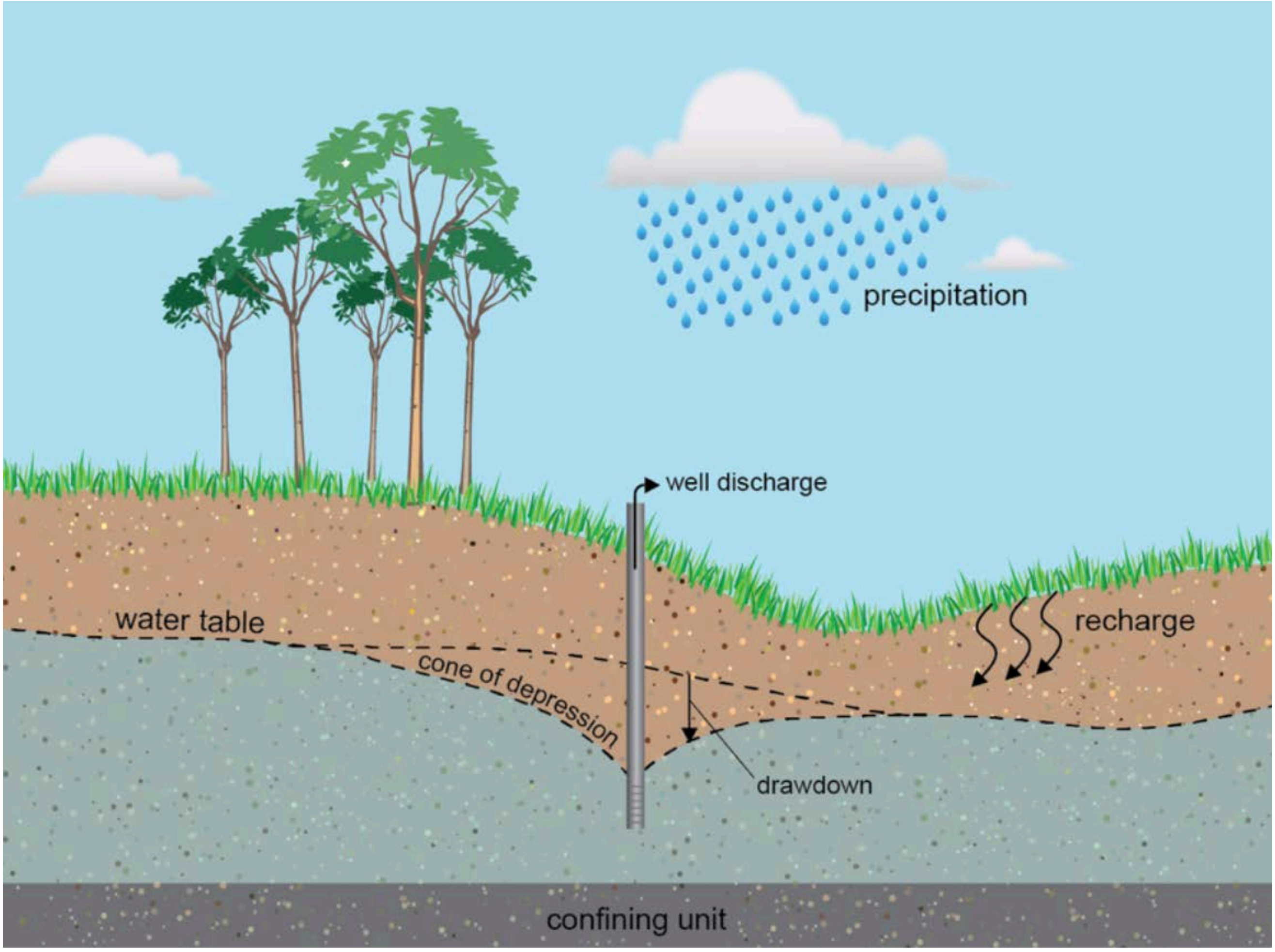


Figure 8-6 *A cone of depression forms laterally away from a pumping well. The radius of influence is defined as that point where the cone of depression flattens to intersect the existing water table. At UMCD, the depth to water is about 20 meters, and the radius of influence envisioned for utilizing minimally- to non-contaminated water is about 15 meters (Gross, 2018)*

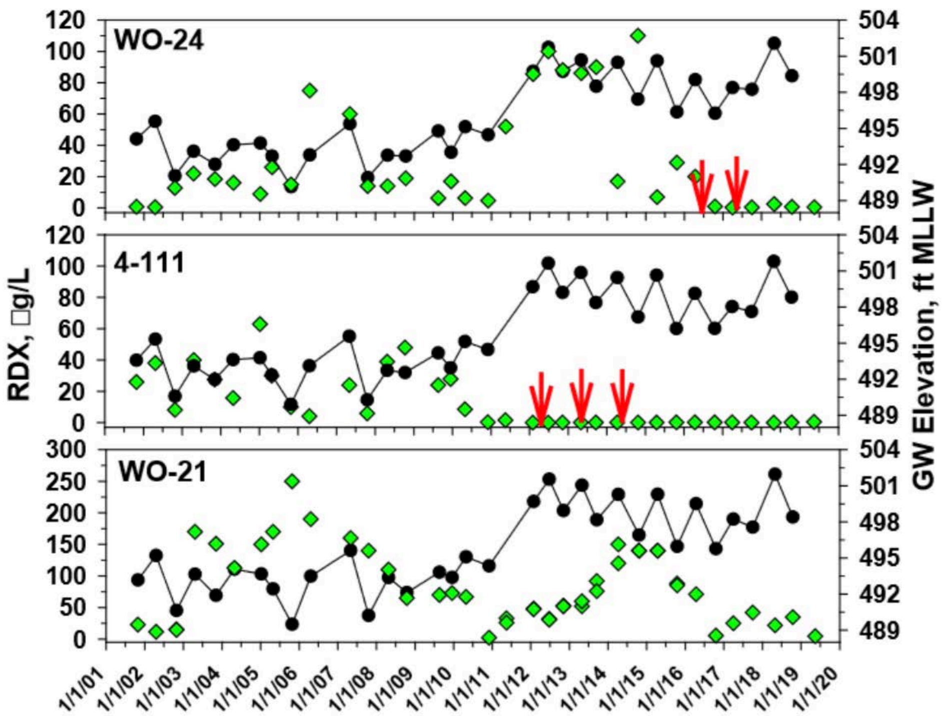


Figure 8-7 *Time-series plots present the progressive decrease in RDX concentrations (green diamonds) over time in the wells presented in Figure 8-5. The black dots represent changes in groundwater elevation over time, and the red arrows depict injection events (Michalsen et al., 2021)*

estimate of capture of water with <2.1 – 10 ug/L RDX; water outside this radius of influence will have increasingly higher concentrations of explosives because it is farther from increased biological activity stimulated by the injectate. Figure 8-6 is a schematic diagram of the cone of depression that forms during pumping and defines the radius of influence of a pumping well.

Figure 8-7 presents time-series plots of the progressive decrease in RDX concentrations (green diamonds) over time in the wells presented in Figure 5. The black dots represent changes in groundwater elevation over time, and the red arrows depict biostimulation injection events (Michalsen *et al*., 2021). Whereas biostimulation involved injection of a mixture of fructose and water, the overall increase in groundwater elevations over time are a result of weather events.

The rough order-of-magnitude cost of three 100-foot wells, groundwater modeling, three episodes of nutrient injection, installation of pumps, laboratory testing and associated labor is $0.75 million dollars (United States dollars [USD]) (Gander, 2020). Periodic biostimulation into the three wells every five years would cost about $0.2 million dollars USD.

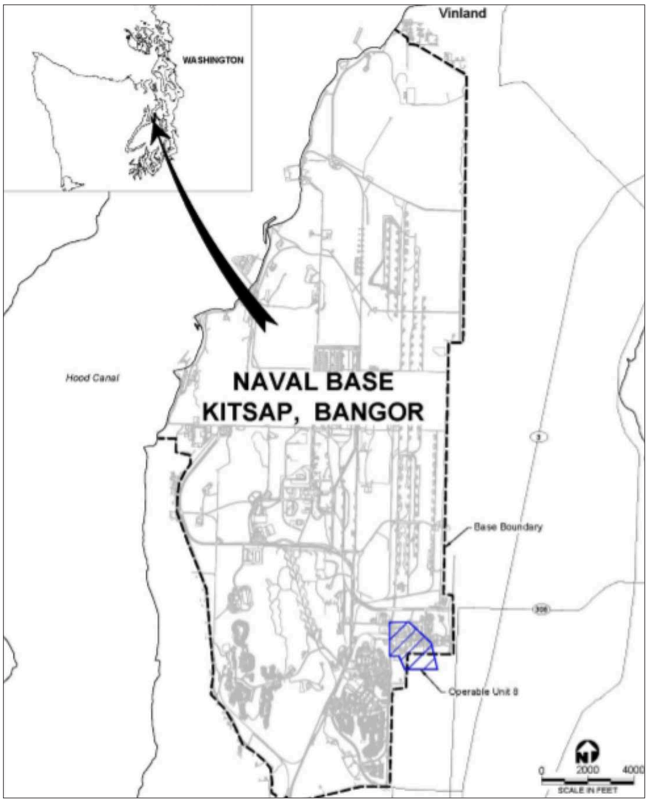


Figure 8-8 ***Location of fuel service station within Operable Unit 8, Washington State, USA (SES, 2018)***

3.2. Solvents in Groundwater

Chlorinated solvents are a large family of organic solvents that contain chlorine in their molecular structure. Since World War II, they have been widely used in the United States and Europe for cleaning and degreasing, and in adhesives, pharmaceuticals, pesticides, and textile processing. The most common forms include carbon tetrachloride, perchloroethylene, trichloroethylene and 1,1,1-trichloroethane.

3.2.1. Chlorinated Solvent Bioremediation at a Fuel Service Station, State of Washington, USA

Summary Statement: At a fuel service station, a suite of common chlorinated solvents has undergone successful bioremediation in groundwater by indigenous anaerobic bacteria. Concentrations below the drinking water clean-up level of 5 ug/L were achieved in 3-5 years in a portion of a larger 1,000 meter groundwater plume. This remediated water could be extracted at a rate of ~ 172 liters per minute (lpm) (45 gallons per minute) in multiple wells and used for drinking water or industrial applications.

3.2.2. Background

The fuel service station, within the area known as Operable Unit 8 (OU 8), is located within the boundaries of Naval Base Kitsap - Bangor, in the town of Silverdale, Washington, United States (Figure 8-8).

In 1986, gasoline from a leaky underground storage tank and associated piping was discovered. An array of groundwater monitoring wells were installed to define the vertical and lateral extent of contamination, and a gasoline (free product) recovery system was installed. Free product refers to actual gasoline that floats on top of groundwater (also referred to as the saturated zone) because it is less dense than water. Between 1986 and 1998, approximately 22,800 liters (6,000 gallons) of free product was recovered. Residual free product and dissolved phase gasoline remains onsite and partially overlaps a small portion of the existing chlorinated solvent ("solvent") plume, which is the focus of this discussion.

Solvents were first identified in 1993. A groundwater pump and treat (P&T) system was installed in 1997 and operated until 2000. The primary objective of the P&T system was to reduce solvent concentrations and prevent further contaminant movement across the Naval base boundary, which was accomplished. A gasoline additive, 1,2-dichloroethane (DCA), is the most prevalent solvent in the plume; others include 1,1,1-trichloroethane (TCA) and 1,1-dichloroethane (DCE).

The current extent of the solvent plume is within the dark circular area in Figure 8-9, and the original extent of the solvent plume is shown by the faint pink circle.

3.2.3. Bioremediation Implementation

Injections of emulsified vegetable oil (EVO) into four closely-spaced wells (not shown) immediately south of 8MW05 were completed in 2010, 2012, and 2017 (Figure 8-9) (SES, 2018). In addition to biostimulation, bioaugmentation was also

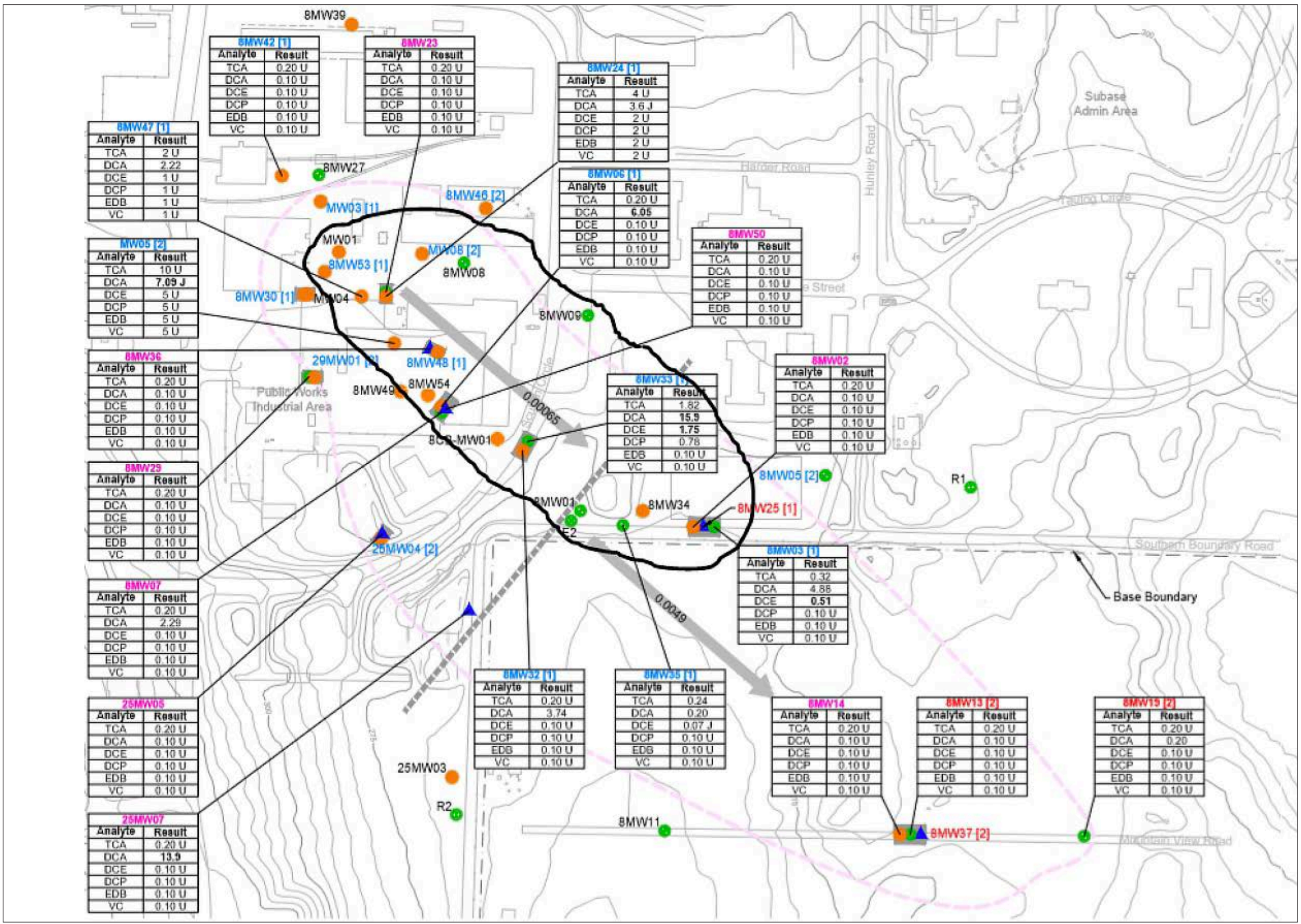


Figure 8-9 *Map showing 2019 solvent concentrations in wells, the footprint of the solvent plume before bioremediation (faint pink circle), and the current solvent footprint (black circle) (SES, 2020)*

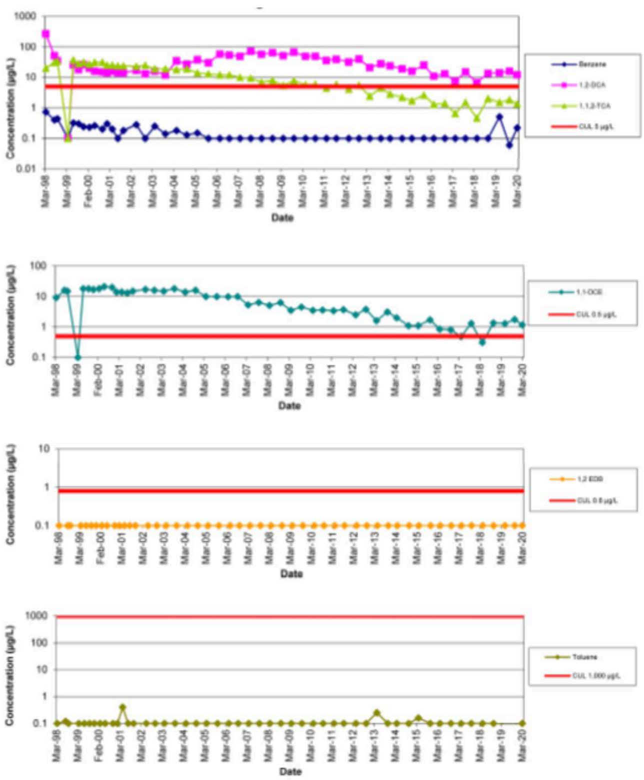


Figure 8-10 *Time-series plots of well 8MW06 before and after biostimulation. Injection of nutrients was conducted in 2010, 2012 and 2017 (SES, 2020)*

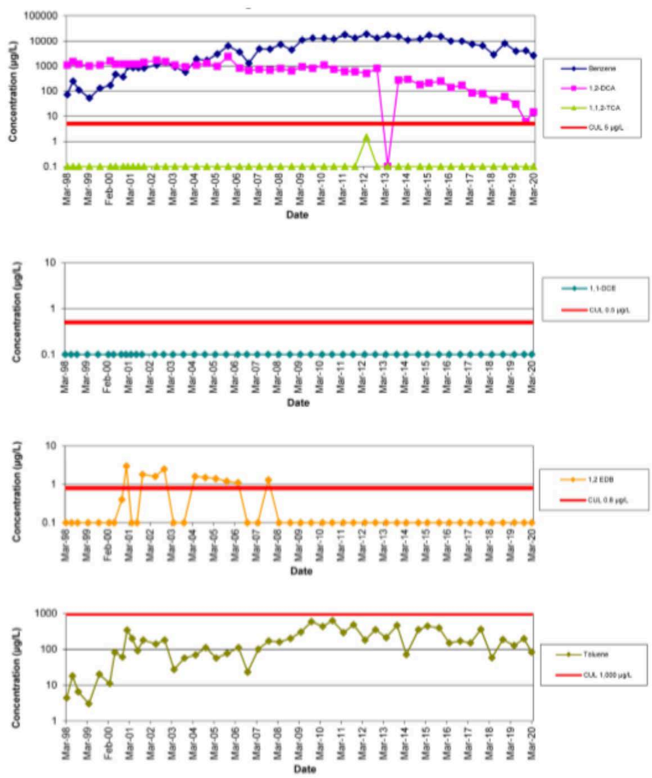


Figure 8-11 *Time-series plots of well 8MW33 before and after biostimulation. Injection of nutrients was conducted in 2010, 2012 and 2017 (SES, 2020)*

conducted in 2010 and 2012 by introducing the anaerobic microbes Dehalococcoides spp. and Dehalobacter spp., which are known to be effective in dehalogenation (dechlorination) and to fully metabolize the solvents to harmless constituents.

Wells 8MW03, 8MW06 (Figure 8-10) and 8MW33 (Figure 8-11) are located hydraulically downgradient of the EVO injection wells, and demonstrate decreasing solvent concentrations that are primarily attributable to the biostimulation events.

Some degree of volatilization of the solvents has occurred since the solvent release in the 1980s, but the groundwater monitoring and attendant laboratory analysis conducted over time since initiating cleanup indicates that bioremediation has significantly accelerated the cleanup by destroying contaminant mass and overall lowering solvent concentrations. For example, in 8MW06 (Figure 8-10), which is about 30 meters downgradient and relatively close to the EVO injection wells, the pink DCA time-series plot shows a pronounced downward trend particularly from 2017 to 2020, likely due to the nutrient injection.

Based on aquifer pump tests conducted in the mid-1990s (FWENC, 1999), pumping rates were established where the groundwater levels remained relatively constant during the pump and treat operation to address the solvent contamination. Given the progress seen by bioremediation in reducing solvent concentrations to below drinking water cleanup levels in a portion of the plume, it is concluded that wells 8MW03 and 8MW33 would be viable candidates as pumping wells for either drinking water or industrial use. Further pumping tests in 2012 (SES, 2018) combined with earlier pump test data indicate that a pumping rate of ~ 172 liters per minute (lpm) (45 gallons per minute) would be effective within a radius of influence of about 12 meters around each pumping well.

Based on the previous work, periodic biostimulation into the injection wells, or wells downgradient with residual contamination, will be effective every five years and would cost about $0.15 million dollars USD.

3.3. Nitrates in Groundwater

Nitrates are the most common groundwater pollutant worldwide (Ross, *et al*., 2010), and the principal sources are fertilizers, followed by human and animal waste. Nitrogen, phosphorus and potassium are the main constituents of fertilizers, and nitrogen from fertilizers is the main source of nitrate pollution (Vance *et al*., 2015). Nitrate is the dissolved form of dissolved nitrogen, which is the main source of nitrogen for plants.

3.3.1. Pump and Fertilize Remediation, Tulare Lake Basin and Salinas Valley, California, USA

Summary Statement: Two large agricultural basins in Central California have extensive nitrate groundwater contamination. Conventional treatment methods (pump and treat using reverse osmosis and ion exchange or biological treatment) are cost prohibitive. Therefore, given the ongoing agricultural activities, it is acknowledged that achieving drinking water nitrate levels (45 mg/L; for comparison, 50 mg/L in European Union) are unnecessary. The focus has become efficient use of the nitrate-bearing groundwater as the basis of application of fertilizer plus animal waste. Nitrate concentrations and nitrate mass are being lowered by pumping and using the existing nitrate-bearing groundwater, adding measured fertilizer and manure, and recirculating the optimally amended water.

3.3.2. Background

The Tulare Lake Basin (TLB) and Salinas Valley (SV) are located in California's Central Valley, USA (Figure 8-12). An ongoing thirty year

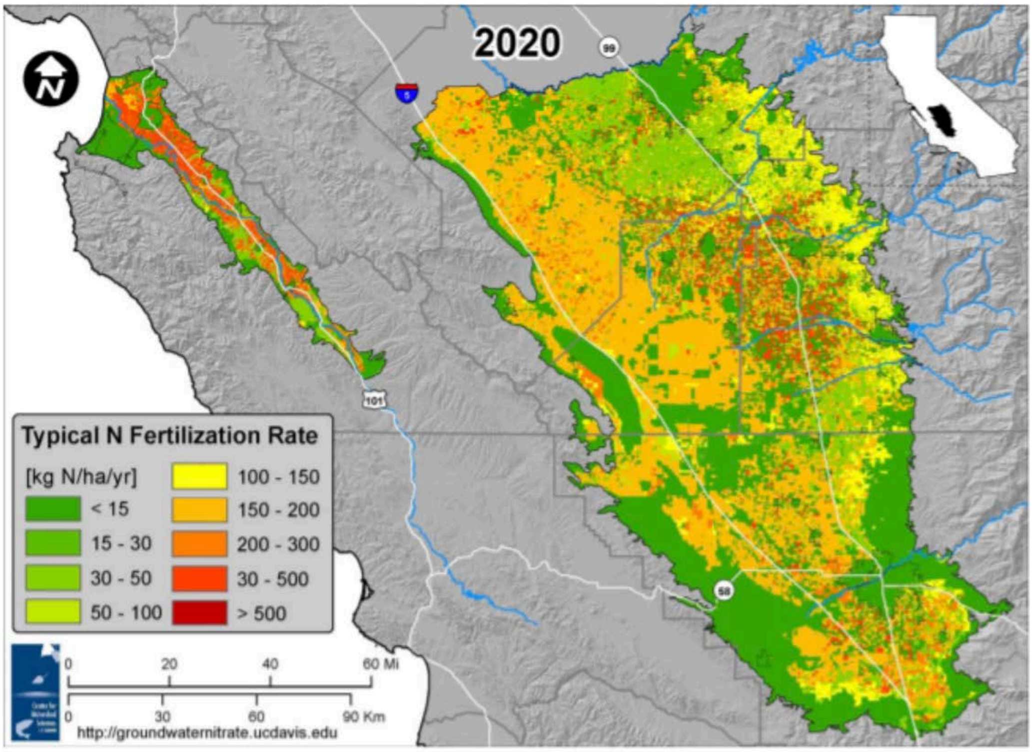


Figure 8-12 *Estimated 2020 nitrogen fertilization rate, Tulare Lake Basin and Salinas Valley, California, USA. (UC Davis, 2017)*

pilot program in agricultural sub-basins of the TLB and SV is assessing the effectiveness of conservatively applying nitrate-bearing groundwater as irrigation water, which is amended with annual additions of fertilizer and animal waste before actual application. The most intensive soil and manure applications occur in an area roughly 4,100 km^2 (Figure 8-12). Formerly, the volumes of water plus fertilizer and manure mixtures were inconsistently or haphazardly applied with minimal forethought, leading to nitrate overloading of soils and substantial leaching to groundwater.

Legislation has been passed that requires all dairy farmers to monitor wells via sampling and analytical testing to help control nitrate loading from manure (CWB, 2013). Funding is being allocated to improve the currently inadequate basin-wide data collection program by developing a nitrate mass balance tracking and reporting system by both cropland farmers and dairy farmers (CWB, 2013).

"In order to reduce future groundwater contamination, improving nitrogen and water management on croplands is critical"

3.3.3. Pump and Fertilize Remediation

In order to reduce future groundwater contamination, improving nitrogen and water management on croplands is critical, given that widespread application of synthetic nitrogen fertilizers is a foundation for California's robust agricultural economy. The five counties that comprise the TLB and SV are among the most agriculturally productive in the United States

Nutrient, soil, and water management practices capable of reducing the impacts of croplands on groundwater quality include optimizing application rates and timing of water, fertilizer, and manure applications to better align with crop need, adjusting crop rotation strategies, improving storage and handling of fertilizers and manure, and tracking manure-nitrogen in order to reduce inorganic nitrogen applications as appropriate (UC Davis, 2012).

Data collection is in progress from the ongoing pilot test regarding the effectiveness of pump and fertilize remediation. Therefore, existing data from nitrate loading from fertilizer and manure, and associated wells, was used to model and predict the impact of existing and future nitrate applications (UC Davis, 2012).

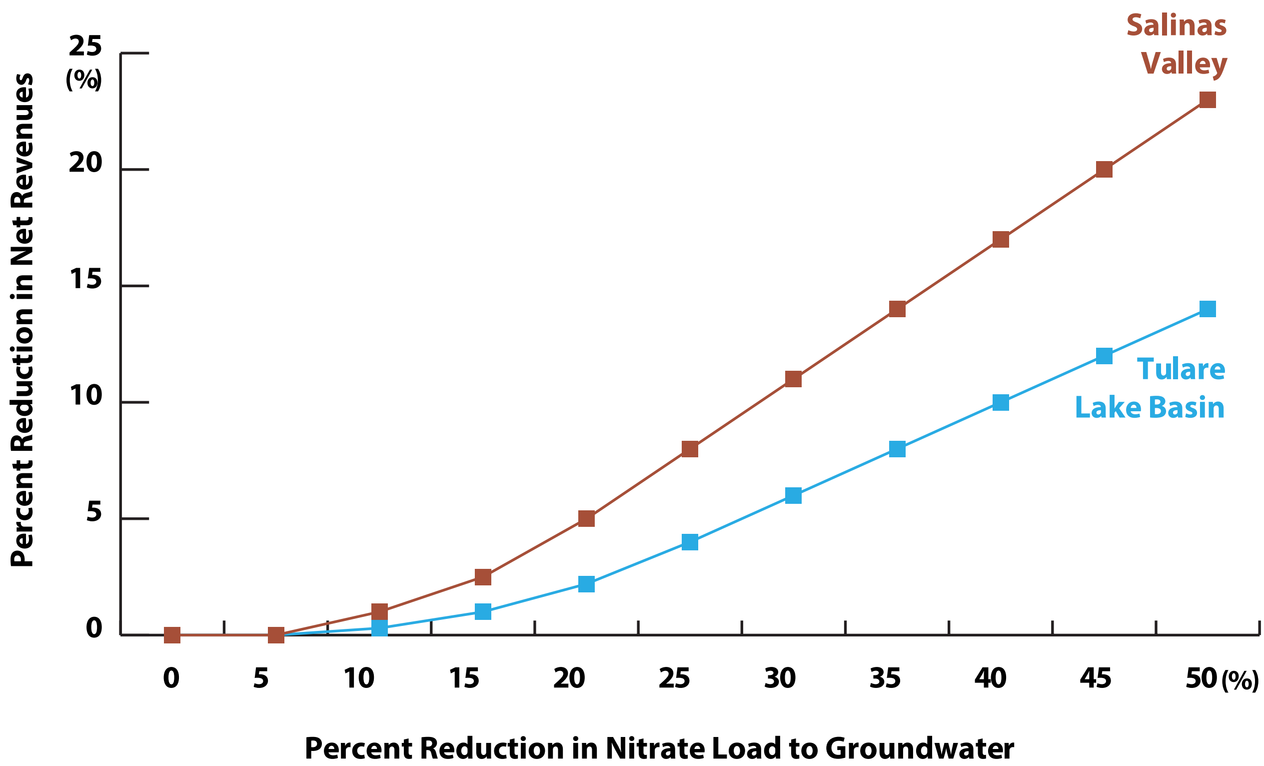


Figure 8-13 *Percentage reductions in net revenue estimated from different levels of reduction in loading to groundwater, Tulare Lake Basin and Salinas Valley, California, USA (UC Davis, 2012)*

The model was designed to assess the economic impact on farmers of policies that reduce nitrate loading from croplands. Because nitrate loading to groundwater in irrigated cropping systems is mainly a function of nutrient and water management, the model is based on economic and environmental consequences of changes in nutrient use and irrigation efficiency. It is assumed that better management costs more money.

The model also assumes that the mass of nitrate leaching to groundwater from irrigated croplands is a function of two pieces of information: 1) the amount of nitrogen applied, times 2) the quantity of water moving beyond the rootzone. The model allows producers to adopt changes to both or either factors.

An important aspect of the model is accounting for nitrate leaching potential, which is based on two metrics: nitrogen use efficiency (NUE), and nitrogen surplus. NUE is defined as the recovery of nitrogen by the crop and nitrogen surplus is the amount of nitrogen that is left behind in soil and becomes available to subsequent crops.

Modeling results indicates that small reductions in nitrate loading to groundwater from croplands can be made at relatively low costs, which is consistent with other studies (Vickner *et al*., 1998; Knapp *et al*., 2008) (Figure 8-13).

The cost of reducing nitrate loading to groundwater from irrigated crop farming appears to more significantly increase with reductions of nitrate volumes of more than 25 percent (Figure 8-13), depending on the true costs of implementing efficiency improving management practices involving: a) changes in nitrogen use efficiency, b) changes in irrigation efficiency, and c) changes in cropping patterns (UC Davis, 2012). Again, the model assumed that better management will be more expensive due to increased infrastructure cost, labor cost, and costs for information and education, but will reduce total nitrate loading from croplands.

The predicted costs to reduce nitrate loading in the TLB and SV can be illustrated if it is assumed an agricultural or dairy farm operation occupying 200 hectacres (500 acres) has a net annual revenue of $100,000 USD. A 15 percent decrease in loading to groundwater will cost $3,000 annually; a 25 percent decrease will cost $7,000; and a 50 percent decrease will cost $17,000 (UC Davis, 2012). The added costs are in large part due to the need to distribute the amended irrigation water more efficiently and involve operation and maintenance labor, additional well installation, and pumps and piping.

Pump and fertilize costs were compared to pump and treat (P & T) costs for a nitrate-contaminated plume area of similar size (500 acres) with similar well depth (75 meters), where biological treatment with P & T is employed (UC Davis, 2012a). A P & T system would require an initial capital outlay of $2,000,000 USD or more, and would require operation for several years (depending on factors such as number of extraction wells in operation and pumping rates) to remove contaminant mass to a level similar to that achieved by the pump and fertilize method of 50 percent loading reduction (UC Davis, 2012a; Gander, 2020). The expected annual operation and maintenance (O & M) costs for the P & T system would be $50,000 - $100,000 USD (Gander, 2020). Although profoundly more expensive, drinking water levels would be achieved, or nearly so, within five to ten years in at least a portion of the plume. Thereafter, a combination of nitrate source control and a reduced pump and treatment scheme would have to be operated to maintain or further reduce the nitrate mass.

In summary, this brief cost comparison shows the two order-of-magnitude difference in these two technologies, and underscores the importance of defining groundwater use objectives and short- and long-term management goals.

04

Groundwater Pollution and Climate Change

The transport and chemical behavior of polluted surface water and groundwater has been well-studied. What has received much less attention is how climate change may alter how pollutants move in the subsurface; how they daylight to surface water bodies or the ground surface; and how the deleterious effects of pollutants may be exacerbated in response to climate change.

The following are examples of how climate change can create pollution, or how climate change affects existing pollution:

-Rising sea levels from climate change coupled with the lowering of freshwater levels in drinking water wells results in seawater intrusion into coastal aquifers, rendering drinking water unsuitable for consumption due to high chloride concentrations. In some areas, climate change will cause drought, which will also increase the negative impact of seawater intrusion on coastal groundwater resources.

- Increased flooding from more intense storms increases the deposition of pollutants in floodplains and low-lying urban areas. This redistribution and concentration of pollutants in surface soils will increasingly leach into groundwater.

- Temperatures are rising due to climate change. Warmer temperatures increase the rate of evaporation of water into the atmosphere, in effect increasing the atmosphere's capacity to "hold" water. Increased evaporation is causing drought in some areas and dropping water levels, but also causing increased precipitation in other areas.

- Climate change is expected to affect recharge, but the effects may not necessarily be negative or decrease in all regions worldwide (Gurdak *et al*., 2010). Recharge is projected to increase in northern latitudes and decrease strongly (e.g., 30-70%) in some semi-arid zones (Doll *et al*., 2008); this effect may be occurring now in South Africa and neighboring countries.

- In some basins, heavy rainstorms induced by climate change have led to increased runoff and decreased aquifer recharge. However, caution must be used in applying sweeping generalizations in all climatic environments about less recharge year-over-year due to more extreme storm events due to climate change. This effect appears real in many surface water/groundwater basins but requires more region-specific study.

Studies by Cuthbert *et al*. (2019) and Owor *et al*. (2009) present data that some aquifers in arid and semi-arid environments significantly benefit from recharge during extreme storm events, perhaps more so than all day rainfall episodes. Here, storm-related runoff is not causing as much of a decrease in groundwater levels as may have been originally hypothesized. Thus, aquifers can show significant resiliency in capturing recharge during extreme storm events. Further, multiple studies indicate that climate change is causing fewer, but more extreme, heavy rain events (Taylor, 2020).

Regional precipitation data and water level data in wells, along with the attendant hydrogeologic setting, must be considered when drawing conclusions about the effects of climate change on recharge.

- In some geologic and climatic settings, higher groundwater levels from increased recharge from more intense heavy rainfall events induced by climate change is also associated with increased diarrheal diseases from bacteria in shallow groundwater-fed water supplies (e.g., wells 5-10 meters deep) and outbreaks of diarrheal diseases in both low- and high-income countries (e.g., Taylor *et al*., 2009).

- Sparse data suggests that overlying soils or bedrock filter some microplastics before concentrating in underlying groundwater (WHO, 2019). Less frequent but more intense monsoonal rains induced by climate change has been shown to be a major contributor to aquifer recharge events in some semi-arid to arid environment aquifers. Therefore, climate change-induced monsoonal rains can not only increase recharge but will also potentially increase the leaching of microplastics (e.g., from pesticides) to aquifers.

- Although poorly documented, the land application of biosolids from waste water treatment plants (WWTPs) serve as potential leachate sources of PFAS and microplastics. Climate change-induced monsoonal rains may increase leaching.

- Decreased recharge creates a lowering of water levels in aquifers. In arsenic-bearing formations, when the saturated zone drops, the oxidation state of arsenic changes (As[III] to As[V]) due to exposure to more oxygen. In formations with the mineral arsenical pyrite, as in Bangladesh, arsenic is released as pyrite oxidizes and dissolved arsenic concentrations are increased, creating a more severe pollution problem in groundwater.

- Certain types of groundwater remediation systems are designed to treat groundwater that is collecting contaminants that have leached to certain depths in the subsurface. When water levels drop substantially (3-5 meters or more) due to climate change, these systems may not have been designed to continue to function at lower water tables and added costs will be incurred for redesign.

05

Concluding Remarks & Policy Recommendations

Monitoring, sustaining water supply volumes, and sustaining or improving various levels of water quality, are fundamental challenges for those charged with managing water security within a limited budget. Policymakers and many water practitioners only have a vague notion of what constitutes drinking water level quality water, or how concentrations of certain naturally-occurring constituents or anthropogenic constituents can be managed or remediated to make the water usable for many agricultural or industrial applications.

This study is intended to raise awareness and educate policymakers and practitioners to ensure they have the technical underpinning to make informed decisions when managing water security with regard to varying levels of water quality. The following are some high-level policy issues and recommendations to address them:

"Countries should move toward a policy of full cost accounting to ensure the market price of plastics reflects the cost of production as well as life cycle management"

Issue: The transport and chemical behavior of polluted surface water and groundwater has been well-studied. What has received much less attention is how climate change may alter the way pollutants move in the subsurface; how they daylight to surface water bodies or the ground surface; and how the deleterious effects of pollutants may be exacerbated in response to climate change, as discussed in this study.

Policy Recommendation: Policy makers need to be aware of how climate influences or exacerbates or creates pollution (see Section 5), particularly with regard to conditions in their own jurisdictions.

Issue: Although data on this subject are incomplete, PFAS (a carcinogen) is widespread in effluent from industrial processes that is discharged to either sewer systems or the natural environment. WWTPs are not analyzing for PFAS in their influent and discharge water is likewise not being analyzed, resulting in discharged PFAS leaching into underlying aquifers. Although banned in some parts of Europe, WWTPs continue to generate vast amounts of biosolids that are spread over agricultural areas or undeveloped areas. These biosolids contain PFAS and there is subsequent crop uptake of PFAS, which is poorly understood, or leaching of PFAS into underlying groundwater.

Policy Recommendation: Industrial facilities should be allocating funds to quantify, via laboratory analysis, PFAS compounds before wastewater effluent is released from their facilities. Although not a source of PFAS, WWTPs inevitably receive influent that contains PFAS from many sources. Even if ongoing sampling and laboratory analysis is not feasible due to a lack of funding from the initial users of PFAS-bearing products, some level of baseline sampling/laboratory analysis can verify the presence of PFAS from effluent from WWTPs, and this will guide the control of effluent or restrict or prohibit land application of biosolids generated by the WWTPs.

Issue: The production of plastics is increasing (Lacy *et al.*, 2019). Plastics are produced by the processing of fossil fuels, which is known to contribute to climate change. About four to eight percent of annual global oil consumption is associated with plastics, according to the World Economic Forum (Lacy *et al.*, 2019). If this reliance on plastics persists, plastics will account for 20 percent of oil consumption by 2059.

Policy Recommendation: This trend must be reversed by the passage of statutory requirements in individual countries that mandate gradual reduction of plastics production. Countries should move toward a policy of full cost accounting to ensure the market price of plastics reflects the cost of production as well as life cycle management (clean up, recycling, reuse, etc.). This recommendation is akin to the Extended Producer Responsibility (EPR) approach, under which producers are given a significant responsibility – financial and/or physical – for the treatment or disposal of post-consumer products.

References

Barboza, L., Viera, L. & Guilmermino, L. (2018).
Microplastics increase mercury bioconcentration in gills and bioaccumulation in the liver, and cause oxidative stress and damage in *Dicentrarchus labrax* juveniles. *Nature Research*, 8, pp. 1-9.

Cuthbert, M., Taylor, R., Favreau, G., Todd, M., Shamsudduha, M., Villhoth, K., MacDonald, A. & Scanlon, B. (2019).
Observed controls on resilience of groundwater to climate variability in sub-Saharan Africa. *Science Daily, August*, www.sciencedaily.com/releases/2019/08/190807131928.htm.

CWB (California Water Boards). (2013). Recommendations addressing nitrate in groundwater.
State water resources control board report to the legislature.

Doll, P. & Fieldler, K. (2008). Global-scale modeling of groundwater recharge. *Hydrology Earth Systems in Science*, 12, pp. 863-885.

EPA (United Stated Environmental Protection Agency). (2001).
Pump and Treat Systems: Summary of Selected Cost and Performance Information at Superfund-financed Sites.
Office of Solid Waste and Emergency Response, EPA-52-R-021b.

______. (2001). Groundwater Pump and Treat Systems:
Summary of Selected Cost and Performance Information at Superfund-financed Sites. EPA 542-R-01-2c 1b.

______. (2020). Pesticide registration, inert ingredients overview and guidance.
https://www.epa.gov/pesticide-registration/inert-ingredients-overview-and-guidance.

FWENC (Foster Wheeler Environmental Corporation). (1999).
Final Groundwater Flow Model Report. *Remedial Action Contract II, Delivery Order 0010*.

Gadd, G. (2007). Geomycology: biogeochemical transformations of rocks, minerals, metals and radionuclides by fungi, bioweathering and bioremediation. *Mycological Research*, 111(1), pp. 3-49.

Gander, M. (2020). Unpublished Operations and Maintenance (O & M) costs for pump and treat systems and bioremediation systems costs for confidential clients.

Gross, t. (2018). Schematic of cone of depression in a pumping well. *United States Geological Survey public domain*.
https://www.usgs.gov/media/images/cone-.depression-pumping-a-well-can-cause-water-level-lowering.

Groundwater Foundation. (2020). Anthropogenic pollution sources.

Gurdak, J. & Roe, C. (2010). Review: Recharge rates and chemistry beneath playas of the High Plains aquifer, USA.
Hydrogeology Journal, 18, pp. 1747-1772.

Hossain, M. & Chowdhury, M. (2020). Microplastic contamination in Penaeid shrimp from the Northern Bay of Bengal. *Chemosphere*, 238, pp. 655-688.

IPCC (Intergovernmental Panel on Climate Change). (2008).
Technical Paper on Climate Change and Water (Finalized at the 37^{th} Session of the IPCC Bureau).
http://www.ipcc.ch/meetings/session28/doc13.pdf.

Koelmans, A., Hazimah, N., Nor, M., Hermsen, E., Kool, M., Mintenig, S. & De France, J. (2019).
Microplastics in freshwaters and drinking water: Critical review and assessment of data quality. *Water Research*, 155, pp. 410-422.

Knapp, K. & Schwabe, K. (2008). Spatial dynamics of water and Nitrogen Management in irrigated agriculture.
American Journal of Agricultural Economics, Agricultural and Applied Economics Association, 90(2), pp. 524-539.

Lacy, P., Spindler, W. & McAndrews, W. (2019). Plastic is a global problem. It's also a global opportunity. *World economic forum*.

Margat, J. & van der Gun, J. (2013). Groundwater around the world. *CRC Press/Balkema*.

Martin, M., Dolven, B., Feichert, A. & Lum, T. (2019).
War Legacy Issues in Southeast Asia: Unexploded Ordnance (UXO). *Congressional Research Service Report, R456749, https://crsreports.congress.gov*.

Martinez, R., Beazley, M. & Sobecky, P. (2014). Phosphate-Mediated Remediation of Metals and Radionuclides.
Advances in Ecology, 2014, pp. 1-14.

Michalsen, M. M., Lalley, J. M., Addis, K. L., Gelinas, S. L. & Istok, J. D. (2021).
Biostimulation achieved rapid RDX degradation and sustained groundwater cleanup level for years, even following RDX addition from contaminatewd vadose zone. *Groundwater Remediation & Monitoring*. Submitted January 2021.

Mintenig, S., Loder, M., Primpke, S. & Gerdts, G. (2019) Low numbers of microplastics detected in drinking water from ground water sources. *Science of the total environment*, 648, pp. 631-635.

Mintenig, S., Int-Veen, I., Loder, M., Primpke, S. & Gerdts, G. (2017).
Identification of microplastic in effluents of waste water treatment plants using focal plane array-based micro-fourier transform infrared imaging. *Water Research*, 108, pp. 365-372.

NGWA (National Ground Water Association). (2017).
Groundwater and PFAS: state of knowledge and practice. *NGWA Press, Westerville, Ohio*.

Owor, M., Taylor, R., Tindmugaya, C. & Mwesigwa, D. (2009). Rainfall intensity and groundwater recharge: empirical evidence from the Upper Nile Basin. *Environmental Research Letters*, 4(3), pp. 3-9.

Panno, S., Kelly, W., Scott, J. & Zheng, W. (2019). Microplastic contamination in karst groundwater systems. *Groundwater*, 57(2).

Pichtel, J. (2012). Distribution and Fate of Military Explosives and Propellants in Soil: A Review in Special Issue, Impact of Human

Activities on Soil Contamination. *Applied and Environmental Science, Volume 2012, Article ID 617236, 1-33*.

Prata, J. (2017). Airborne micropklastics: Consequences to human health. *Environmental Pollution*, 234, pp. 115-126.

Rosansky, S. (2020). Personal communication regarding supercritical water oxidation processing rates. *Battelle Memorial Institute, July 6*.

Ross, N. (ed.). (2010). Clearing the waters, a focus on water quality solutions. *United Nations Environmental Programme*. ISBN-978-92-807-3074-6, Nairobi, Kenya.

SES (Sealaska Environmental Services), LLC. (2018). Biotreatment Barrier Maintenance Report, *Contract N44255-14-D-9011, Task Order 52*.

______. (2020). Round 42 (Spring 2020) Monitoring Report, Monitored Natural Attenuation/Operable Unit 8 at Naval Base Kitsap Bangor, Silverdale, Washington. Contract N44255-14-D-9011, Task Order N4425519F4121.

Smith, M., Cross, K., Paden, M. & Laban, P. (2016). Spring – Managing groundwater sustainability. *IUCN, Gland, Switzerland*. https://www.ngwa.org/what-is-groundwater/About-groundwater/facts-about-global-groundwater-usage.

Strand, J., Field, L., Murphy, F., Mackevica, A. & Hartmann, N. (2018). Analysis of microplastic particles in Danish drinking water. *Scientific report 293 from Danish centre for environment and energy.*

Taylor, R. (2020). Personal communication regarding the relationship between climate change and extreme storm events. *August 12*.

Taylor, R., Miret-Gaspa, M., Tumwine, J., Mileham, L., Flynn, R., Howard, G. & Kubako, R. (2009). Increased risk of diarrhoeal diseases from climate change: evidence from urban communities supplied by groundwater in Uganda. *Groundwater and Climate in Africa. Proceedings of the Kampala Conference, Uganda*, 24-28, 15-19.

USACE (United States Army Corps of Engineers). (2015). Fourth Five Year Review, Morrow and Umatilla Counties, Oregon. *Unites States Army Corps of Engineers Seattle District, Seattle, Washington*.

UC Davis (University of California Davis). (2012). Nitrogen source reduction to protect groundwater. Groundwater remediation and management of nitrate with a focus on Tulare Lake Basin and Salinas Valley groundwater, Technical report 3. Report for the state water resources control board report to the legislature.

______. (2012a). Groundwater remediation. Groundwater remediation and management of nitrate with a focus on Tulare Lake Basin and Salinas Valley groundwater, Technical report 5. *Report for the state water resources control board report to the legislature*.

______. (2017). Nitrogen sources and loading to groundwater with a focus on Tulare Lake Basin and Salinas Valley groundwater, technical report 2. *Report for the state water resources control board report to the legislature*.

Vance, D., Neary, L., Sueker, J. & Nelson, D. (2015). Nitrate Remediation: The Importance of the Advanced Nitrogen Cycle in Remedy Selection. *Remediation Journal*, 26(1).

Vickner, S., Hoag, D., Frasier, W. & Ascough, J. (1998). A dynamic economic analysis of nitrate leaching in corn production under nonuniform irrigation conditions. *American Journal of Agricultural Economics*, 80(2), pp. 397-408.

Water Encyclopedia. (2020). *Pollution of Groundwater*. http://www.waterenecylopedia.com/Oc-Po/Pollution-of-Griundwater.html.

WHO (World Health Organization). (2019). Microplastics in Drinking Water. *World Health Organization, License: CC BY-NC-SA 3.0 IGO, Geneva*.

Ziajahromi, S., Neale, P., Rintoul, L. & Leusch, F. (2017). Wastewater treatment plants as a pathway for microplastics: Development of a new approach to sample wastewater-based microplastics. *Water Research*, 112(1), pp. 93-99.

V

Transboundary Aquifer Management

©zabanski/Shutterstock.

9

A Governance Panorama of an Aquifer in a Semi-arid Region, Mexico

Frida Cital, Alfonso Rivera, Eliana Rodríguez-Burgueño and Jorge Ramírez-Hernández

Frida Cital, Universidad Autónoma del Estado de Baja California, Instituto de Ingeniería, Baja California, Mexico.
e-mail: frida.cital@uabc.edu.mx
Alfonso Rivera, Geological Survey of Canada, Quebec, QC, Canada.
e-mail: alfonso.rivera@canada.ca
Eliana Rodríguez-Burgueño, Universidad Autónoma del Estado de Baja California, Instituto de Ingeniería, Baja California, Mexico.
e-mail: eliana.rodriguez@uabc.edu.mx
Jorge Ramírez-Hernández, Universidad Autónoma del Estado de Baja California, Instituto de Ingeniería, Baja California, Mexico.
e-mail: jorger@uabc.edu.mx

Abstract

It is estimated that one third of the groundwater resources of the world are in precarious conditions, with water-quality deterioration, water shortages and other issues. These point to inefficient management practices and an overall lack of adequate governance of this precious resource. In this context, a case of interest is the aquifer of the Mexicali Valley, located in northern Mexico with hydrological transboundary connections with the other side of the Mexico-US international border in the States of California and Arizona.

Previous studies in the region have shown aquifer overexploitation, deterioration of water quality and decrease in aquifer recharge. These problems reflect management issues including a lack of binational management, poor water-management practices by agricultural users, and insufficient systematic monitoring of groundwater quantity and quality. Diverse management instruments have been applied, however, these have not been enough to solve groundwater-related problems.

This chapter analyzes the groundwater availability and sustainability of the Mexicali Valley Aquifer (MVA), their current governance and management practices through the systematic review of legal and institutional frameworks, the implemented management mechanisms, and the binational cooperation.

The largest user of the MVA is the agricultural sector (76% of estimated volume extracted), whose extractions are not quantified. The groundwater use regime is not sustainable, the aquifer loss of storage and depletion increases between 0.5 and 1 m annually. Moreover, international treaties do not include the sharing of water resources on an aquifer scale and are minimally considered in the minutes derived of these treaties.

To cope with these issues, it is recommended to prepare monitoring protocols of groundwater extractions and made periodic measurements of water level, and changes in storage and water quality, to ensure accurate water balances for informed aquifer management decisions.

Keywords

Governance, groundwater, management, aquifer, Mexicali Valley

01 Introduction

Water security is one of the main challenges of the 21st century. Since 2012, it is considered one of the five main social risks in terms of impact (World Economic Forum, 2019), which then underpins all sectors' growth (social, agricultural, energy and industrial) (Dell'Angelo *et al*., 2018). This precious natural resource is indeed being stressed by many compelling factors, such as climate change, population growth and other anthropogenic activities, all of which increase the risk of water scarcity, especially in arid zones. Therefore, identifying and understanding current and future risks of water are important in the decision-making process in the management and governance of this resource (Nair, 2016). This is particularly the case for groundwater, which represents 97% of the available freshwater in the world and is the main source of water for one third of the world's population (FAO, 2016b).

> *"Identifying and understanding current and future risks of water are important in the decision-making process in the management and governance"*

Historically, groundwater has provided between 25 to 40% of water for domestic, industrial, agricultural, and environmental activities (FAO, 2016b), however trends of the existing capacity to extract groundwater demonstrated the limited of volume available for different uses. Currently, technological advances in drilling, pumping and the investigation of hydrogeological conditions have generated the so-called "Silent Groundwater Revolution", during which groundwater extraction increased up to 300% from 1960 to 2010 (FAO, 2016b). This situation has generated important benefits, especially economic, but has also had negative effects on the groundwater reserves (Gleeson *et al*., 2012; Margat & van der Gun, 2013).

Despite the importance of groundwater, in some regions of the world, the monitoring is null and its management poor (Famiglietti, 2014). As a result, water governance has been applied as a support structure to address water needs (Villholt & Conti, 2018). However, governance approaches are still in development and whether the provisions are adequate and effectively implemented must be investigated (Foster & Garduño, 2013; UNESCO, 2012). Meanwhile, most of the main aquifers are suffering negative effects such as decrease in water table (Richey *et al*., 2015), deterioration of water quality, decrease in crop yields, sea water intrusion, degradation of ecosystems, and land subsidence (Chen *et al*., 2016; Shah *et al*., 2001). Subsidence, for instance, has affected large cities, including Tokyo, Bangkok, Jakarta, Venice, San Francisco, and Mexico City (FAO, 2016a).

Like other areas of the world, such as India, Pakistan and Saudi Arabia, Mexico is not exempt from problems related to groundwater (Gleeson *et al*., 2012). Total groundwater withdrawal in Mexico represents 39% of the freshwater used in the country representing all uses combined (CONAGUA, 2018c). Groundwater extraction has been steadily increasing over the last decades and the pumping rates are so high that Mexico is listed as one of the top 10 countries with the highest extraction rates of groundwater per year (Vrba & van der Gun, 2004).

In Mexico, one of the initial measures implemented for groundwater resources management was the geographic delimitation of natural hydrogeological units into 653 administrative aquifers areas. Currently, 105 of these aquifers have a condition of overexploitation, 32 have saline soils and brackish water, 18 have salinity intrusion (CONAGUA, 2018c). Of the 653 aquifers, 18 are transboundary aquifers (11 on the northern border with the United States and 6 on the southern border with Belize and Guatemala), of which 6 have some condition of overexploitation and 7 have saline soils, brackish water presence or marine intrusion (UNESCO, 2015).

One of the most important transboundary aquifers along the Mexico-US border is the Mexicali Valley Aquifer (MVA), which is located in the Colorado River delta. The US-Mexico International Treaty of 1944, assigned surface water from the Colorado River to Mexico at a volume of 1,850 hm^3/yr. However, since the 1950s when the irrigation surface increased in the MVA, the amount described in the treaty became a limitation for development. This limitation prompted an important increase in well drilling in the Mexican portion of the transboundary aquifer during 1955 and 1959 for irrigation purposes. This uncontrolled pumping began to affect the water levels in the Mexicali Valley, creating a continuous decrease.

This review article discusses the insights of the Mexican legislation, water laws, institutions, programs, and plans, as they relate to groundwater on the Mexican-side of the MVA. The work discusses existing practices of groundwater governance of the Mexicali Valley Aquifer.

This paper is mainly focused on the Mexican-side of the much larger transboundary aquifer of Lower Colorado River Basin. Other aspects and effects of the transboundary nature of the MVA are currently under study with a unified hydrogeological conceptual model. In that study, a conceptual framework is proposed integrating data and information from both sides of the international border, and it will be published separately (Cital *et al*., 2021).

02
Study Area

The geohydrological extension of the Lower Colorado River Basin Aquifer (a transboundary aquifer) is 29,800 km^2.
It covers parts of the California and Arizona states in the USA, and Baja California and Sonora in Mexico (Figure 9-1), which corresponds to part of the Imperial, Yuma, Mexicali Valley and San Luis Rio Colorado Valley aquifers, respectively.

The study area is in the northwestern side of Mexico and southeastern part of the United States. The Mexicali Valley Aquifer (MVA) administrative area is 4,908 km^2 located in Baja California; it is limited to the north by the border with the USA, to the west by the Laguna Salada, and to the east by San Luis Rio Colorado, Sonora.

This region is characterized by extreme weather, having long dry periods. The temperature varies between 0°C and 50°C. Average annual precipitation is low (65 mm per year) in contrast to the average potential evaporation that exceeds 2,300 mm per year (CONAGUA, 2015a). Consequently, aquifer recharge by precipitation is practically nil (Feirstein *et al.*, 2008, Rodríguez-Burgueño, 2017). In the study area there are two main sources of water: 1) the Colorado River, governed through the International Treaty of 1994; and, 2) the Mexicali Valley Aquifer.

The most important economic activity in the study area is agriculture, where cyclical and perennial crops are developed, making this region one of the most important irrigation districts in Mexico. The main crops are cotton, wheat, and, to a lesser extent alfalfa, corn, and asparagus (CONAGUA, 2015a). The irrigation district is called 014 Rio Colorado and is made up of 22 irrigation modules (Figure 9-1).

The floodplain of the Colorado River in the MVA is a 1,000-meter-thick layer of recent unconsolidated granular materials, mainly silts, sands, clays, and gravels from the Holocene (Olmsted *et al.*, 1975).

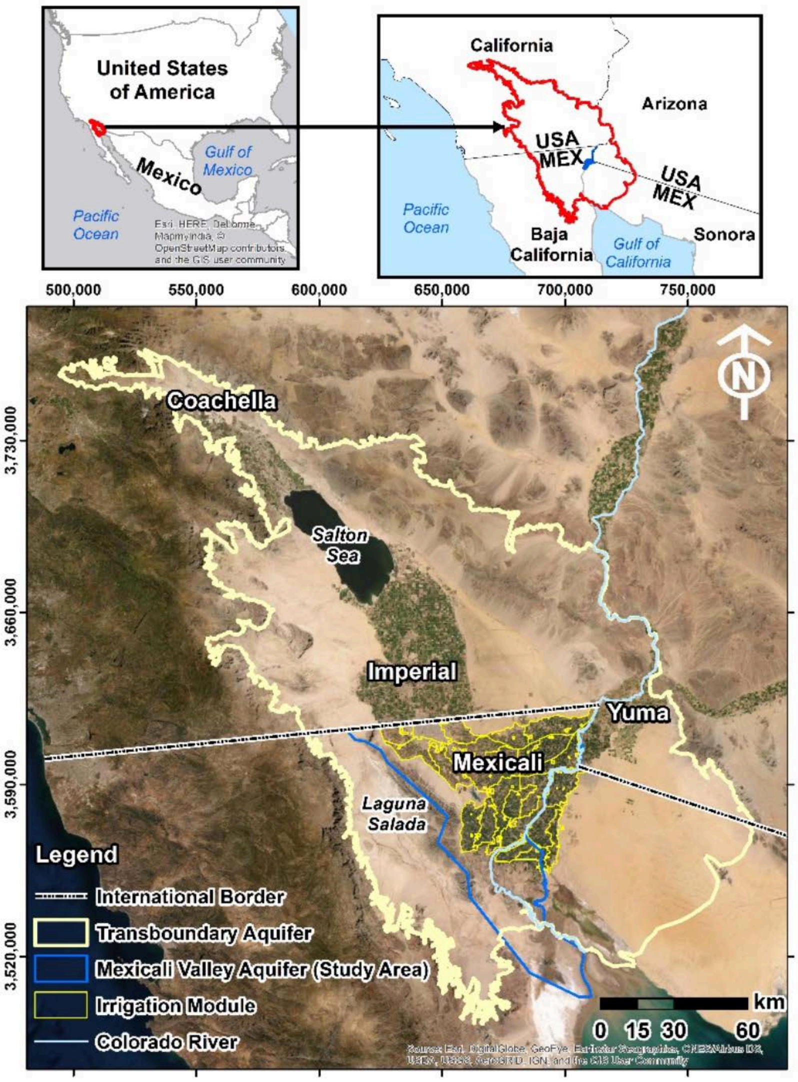


Figure 9-1 Study area. Data (Source: Ramírez-Hernández, 2020; CONAGUA, 2015b)

03

The Mexicali Valley Aquifer

The Mexicali Valley aquifer (MVA) is a portion of the Lower Colorado River Basin transboundary aquifer. The MVA stands out for being one of the most productive aquifers in Mexico. It supplies five of the six municipalities in Baja California (Mexicali, Tecate, Tijuana, and Rosarito) and the agricultural valleys of Mexicali (MV) and San Luis Rio Colorado (SLRC). The MVA presents two precarious conditions: groundwater overexploitation; and, the presence of saline soils and brackish water (CONAGUA, 2018c).

Previous studies carried out in the MVA show the consequences of overexploitation, deterioration of water quality, and decreasing recharge (Cázares, 2008, Cortez-Lara, 1999; DOF, 2018; Feirstein *et al*., 2008; Rodriguez-Burgueño, 2012; Rodríguez-Burgueño, 2017). In relation to groundwater governance, the problems are: 1) lack of a binational and regional water management; 2) consequences of poor water-management practices by agricultural users; 3) the transfer of water concessions between different sectors; and 4) the lack of systematic measurements of the volume extracted from the aquifer (Caballero, 2014; Cortez-Lara, 1999). As a result, the water balance of the MVA is imprecise and based on old data (Table 9-1).

Given the prevailing problems, the National Water Commission (CONAGUA) has applied management measures, such as the promulgation of Aquifer Protection Act in 1965, fixation of the pumping rates, and restricted pumping areas (known in Mexico as zonas de veda) (Sanchez & Eckstein, 2017). However, these efforts have not been enough to constrain overexploitation and water quality deterioration. Other initiatives have been the establishment of participation mechanisms such as the Basin Councils.

Without knowing the precise volume of groundwater recharged and stored in an overexploited aquifer, the increased demand from users in the future is unsustainable (GWP & INBO, 2009). Therefore, it is important to carry out an analysis of the current governance and management of the MVA and identify possible management tools that can contribute to solving the current groundwater issues.

3.1. Groundwater Pumping and Use

The groundwater pumping in the MVA from its inception has never been measured systematically; the data available correspond to approximate estimates made from groundwater concessions. The pumping in the study area started in 1950 with a volume of 780 hm^3/yr; with the development of agricultural lands, this volume increased to 1,100 hm^3/yr. This trend only lasted 8 years as negative effects were observed (Ariel Construcciones S. A., 1968).
To minimize these negative effects Ariel Construcciones S. A (1968) proposed to decrease groundwater extraction and the definition of areas for new wells in the Valley.

The estimated volume extracted decreased to 893 hm^3/yr where it remained for 30 years, approximately. In 2018, that volume increased again to 1,019 hm^3/yr (DOF, 2018). The historical trend of groundwater pumping in the Mexican portion of the aquifer (Mexicali Valley and San Luis Rio Colorado aquifers) is shown in Figure 9-2.

In relation to the uses of water, agricultural stands out as the largest user of groundwater in the MVA. According to the Public Registry of Water Rights (REPDA), in 2018 the volume of water allocated for consumptive uses was 783 hm^3/yr. Seventy-six percent (76.1%) of that volume is used by agriculture, 12% by industries, 11.2% by urban use;

Table 9-1 Official data on the groundwater balance from CONAGUA (2007; 2009; 2010; 2013; 2015a; 2018a; 2020)
** Data not shown in the groundwater balances by CONAGUA.*

Year	Mean annual recharge (hm^3/yr)	Extracted groundwater volume (hm^3/yr)	Designated groundwater volume (hm^3/yr)	Groundwater deficit (hm^3/yr)
2007	520.5	602	892.95	-374.95
2009	520.5	602	1005.98	-487.98
2010	520.5	602	982.65	-464.65
2013	520.5	602	982.65	-464.65
2015	520.5	602	974.04	-456.04
2018	520.5	*	783.12	-265.12
2020	520.5	*	775.96	-257.96

domestic, livestock, and other uses represent only 0.74% (REPDA, 2018). However, it is important to note that 174,358 hm^3/yr of groundwater for urban uses in Ensenada, Tijuana, Tecate and Mexicali in Baja California are imported from the adjacent Mesa Arenosa aquifer in the San Luis Rio Colorado in Sonora (CONAGUA, 2014). The efficiency of conveyance and distribution to the major user, Irrigation District 014, is 40.15% (SEMARNAT & IMTA, 2020) because more than 50% evaporates, infiltrates and is lost in other conveyance factors.

3.2. Water Balance

Estimates by Ariel Construcciones S. A (1968), Díaz (2001), and Rodriguez-Burgueño (2012) reveal that the main source of recharge to the MVA was due a direct vertical infiltration in the distribution channels and agricultural lands.
The rest comes from horizontal flow from the Baja California-California and Arizona borders, Mesa Arenosa of SLRC, and by the All-American Canal. The outputs correspond mainly to groundwater pumping, groundwater discharge along the northern and southern borders and surface discharge to the New, Hardy, and Colorado Rivers (Ariel Construcciones S. A., 1968; Díaz, 2001; Rodriguez-Burgueño, 2012). Due to the lack of systematic devices to measure pumping rates in the wells, the volume extracted from the aquifer is not precisely known.

3.3. Groundwater Availability and Sustainability

Two indicators have been used to measure the availability of groundwater in the MVA. The first indicator is the Relative Water Demand (RWD) described in Equation 9-1, as proposed by Weiskel *et al.* (2007). This is used for measuring the depletion of groundwater storage in a groundwater system and the outflow caused by elevated rates of withdrawal in relation to a renewable supply (Rivera, 2007).

$$RWD = \frac{Hout - Hin}{Rsw + Rgw + (Rp - Det)} \qquad \text{Equation 9-1}$$

where H_{out} is the human withdrawal from the aquifer; H_{in} is the flow returned to the aquifer after human use; R_p is the aquifer recharge from precipitation; R_{sw}+R_{gw} is the aquifer recharge from adjacent surface- and groundwater systems; and is the loss to evaporation.

RWD values near zero indicate a low degree of human-induced flow stress on natural systems. Values higher than one indicate that the net withdrawals exceed natural inflows, denoting water-use regimes that are likely to be unsustainable over the long run (Rivera, 2007).

Using data from the mean water availability in the Mexicali Valley Aquifer for 2015 (CONAGUA, 2015a), the RWD indicator results in equation 9-2.

$$RWD = \frac{783.13 - 515}{140 + (0 - 11)} = 2.07 \qquad \text{Equation 9-2}$$

(Data from CONAGUA, 2015a)

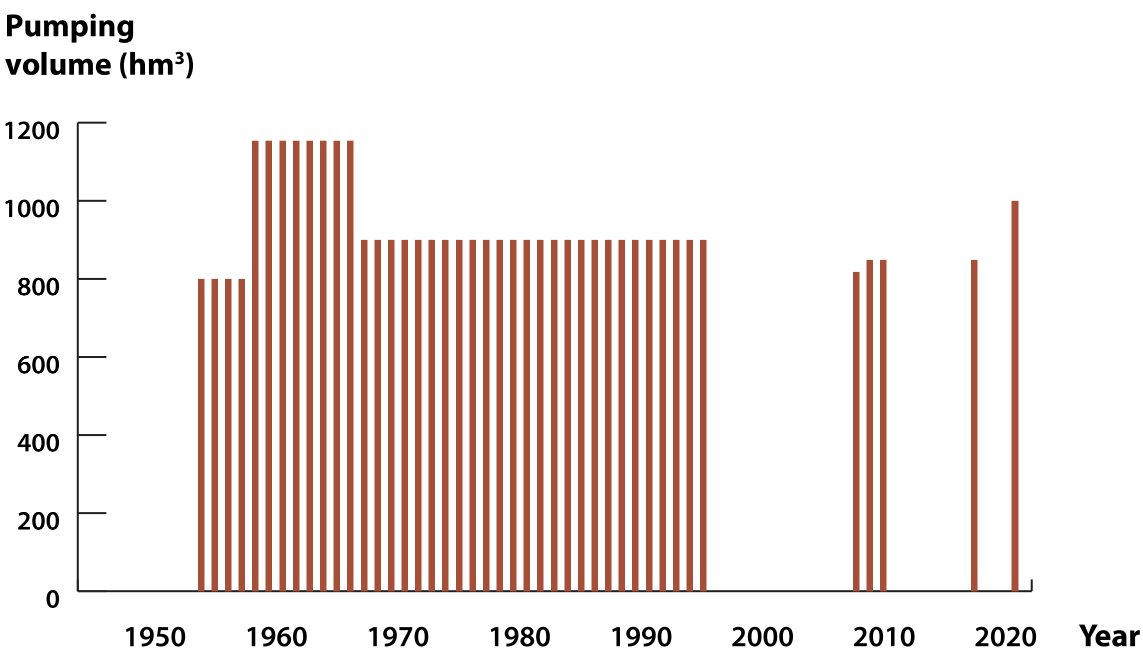


Figure 9-2 *Historical groundwater allocated volume in the Mexican portion of transboundary aquifer in the Mexicali Valley aquifer. Data (Sources: Ariel Construcciones S. A., 1968, CONAGUA, 2015a; 2018b, DOF, 2018)*

The value 2.07 indicates that the water use regime is not sustainable in the study area. This value is even greater than the one for the Mexico City aquifer where the RWD is 1.7, one of the highest water-stressed aquifers in Mexico.

The second indicator is the Storage Change Index (SC) proposed by Weiskel *et al.* (2007), which measures the degree to which a hydrologic system has equilibrated with an imposed set of natural and human stresses during a specific period, shown in Equation 4-3 (Rivera, 2007). Negative values of SC indicate conditions of storage depletion, and storage accretion is reflected in positive values of SC.

$$SC = \frac{\Delta S/\Delta t}{Hout - Hin} \qquad \text{Equation 9-3}$$

where ΔS: is the rate of change of aquifer storage, where all flows are averaged over Δt; and Δt is the time period under consideration.

Using official information from CONAGUA for 2015 in the study area, the SC results in -0.35 (Equation 9-4), which indicates a loss of storage in the MVA. This situation has been reflected in the aquifer depletion which is between 0.5 to 1 m annually.

$$SC = \frac{-95}{783.13 - 515} = -0.35 \qquad \text{Equation 9-4}$$

(Data from CONAGUA 2015a)

04

Groundwater Governance in the MVA

The water governance is composed of legal, institutional, hydraulic, and environmental regulatory frameworks; a social participation mechanism plays an important role too (Murillo-Licea & Soares-Moraes, 2013). This section describes the legal and institutional frameworks, implemented management mechanisms, and binational cooperation in the study area.

Figure 9-3 Law and regulations applicable to the groundwater in the study area (graphical description by the authors)

4.1. Legal Framework

The legal framework is based on the principle established in Article 27 of the Political Constitution of the United Mexican States which declares that the waters of the territory, including groundwater and others, are owned by the Nation. The Federal Government (Executive) via the National Water Commission (CONAGUA), is the organization that can regulate groundwater extraction, use, and establishment of restricted pumping areas (zonas de veda).

As a Republic, the States and municipalities have their own laws too. The applicable laws regarding the management, administration, and protection of water resources are listed below.

Figure 9-3 Law and regulations applicable to the groundwater in the study area. (graphical description by the authors)

In the laws and regulations in Figure 9-3, the activities by every governmental institution are well defined. These include rights and obligations of the government institutions and water users, as well the mechanisms of water management; some of them include regulation for the protection of water quality. However, none of these regulations in force is specific to groundwater.

4.2. Institutional Framework

In Mexico, the institutional framework of water administration and management is centralized. The National Water Commission (CONAGUA) is the main regulator of the Department of Environment and Natural Resources (SEMARNAT). CONAGUA operates and applies the public laws in matters of management of national waters and it is the main water agency that provides groundwater concessions and supervises the protection of water quality in accordance with National Water Law (LAN).

The International Boundary and Water Commission (IBWC) is the binational Mexico-United States agency that works with territorial limits, surface and groundwater, water quality, water sanitation, and projects related to international crossings between Mexico and the United States (GobMex, 2014).

In Baja California, the recently created (2020) Secretary for the Management, Sanitation and Protection of Water (SEPROA) is responsible for designing and coordinating public policy on the management of water resources, as well as the use of water (Periódico Oficial del Estado de Baja California, 2020). The State Water Commission (CEA) administrates the Rio Colorado-Tijuana aqueduct and regulates, organizes, and

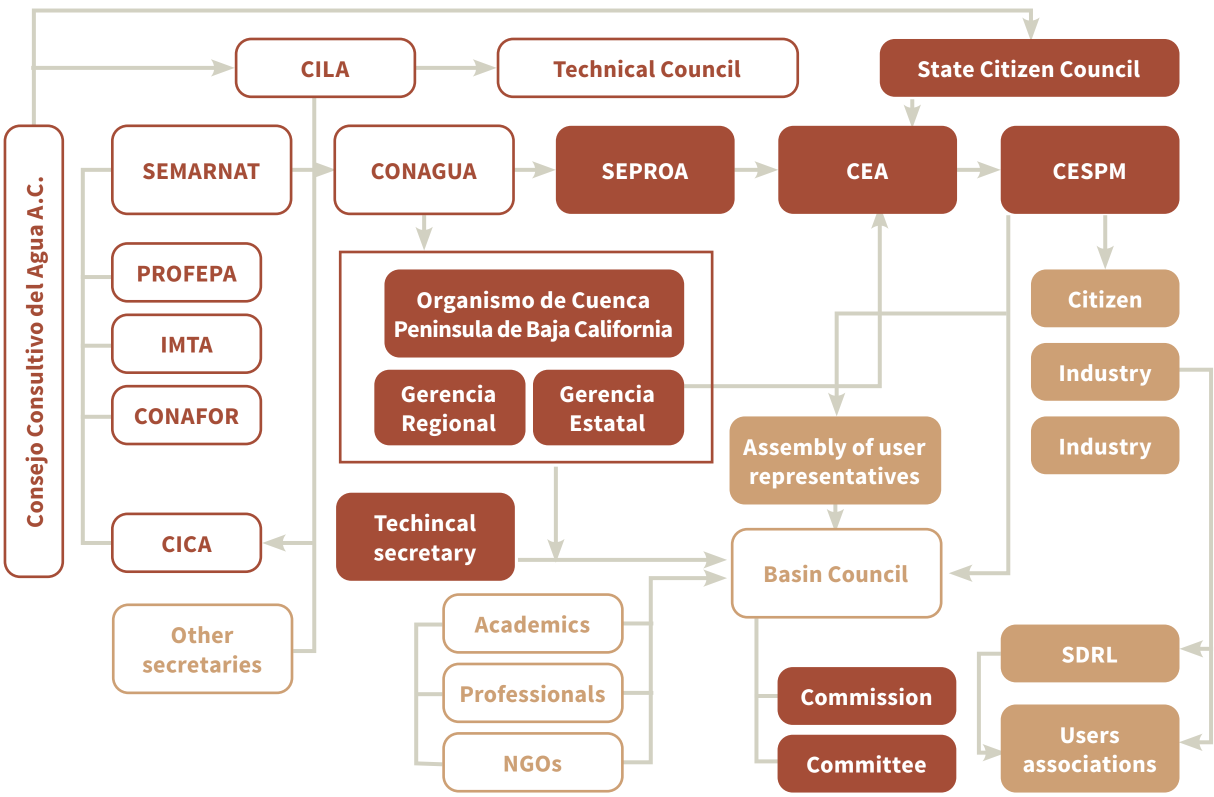


Figure 9-4 *Operating scheme of the water administration and management institutions in Mexico. Modified from Constantino et al. (2011) (CILA: International Boundary and Water Commission; SEMARNAT: Department of Environment and Natural Resources; PROFEPA: Federal Attorney Office of Environmental Protection; IMTA: Mexican Institute of Water Technology; CONAFOR: National Forest Commission; CONAGUA: National Water Commission; CICA: Water Information and Consultation Center; SEPROA: Secretary for the Management, Sanitation and Protection of Water; CEA: State Water Commission; CESPM: State Commission of Public Services of Mexicali, and SDRL: Limited Responsibility Society.)*

executes water policy in the state of Baja California and the hydraulic infrastructure for this purpose (CEABC, 2020). The State Commission of Public Services of Mexicali (CESPM) is a decentralized organization of the State Government; it is in charge of attending the planning, construction, operation and maintenance of the drinking water and sanitary sewer systems (CESPM, 2020). However, Article 115 in the Political Constitution of the United Mexican States establishes that the governments of municipalities should manage the water services in the cities (Consititucion Politica de los Estados Unidos Mexicanos, 1917), thus, in Baja California this article does not apply.

In the Mexicali Valley, the Irrigation District 014 Rio Colorado is made up of 22 irrigation modules (a module is a geographical area where water is delivered to users of the same user organization; these modules manage, operate and conserve hydraulic infrastructure within their area boundaries). The District has hydraulic infrastructure for surface and groundwater (725 wells) and an irrigation network (channels and drains). The Limited Responsibility Society (SDRL), which operates the wells and the major irrigation network, consists of the presidents of the user associations (modules), who oversee managing and operating the minor irrigation and drainage network.

On the other hand, the Basin Councils are made up of members from academe, NGOs, governmental, and non-governmental institutions, society representatives, and others. The Councils are responsible for coordination, agreement, support, consultation, and advice between CONAGUA, the agencies, entities of the federal, state or municipal instances, the representatives of water users, and associations of the society of the corresponding administrative hydrological region (LAN, 2020). Figure 9-4 shows the relations between the institutions. Nevertheless, these inter and intra-institutional relationships do not always proceed in practice and the decision-making process is sometimes unilateral.

> *“Nevertheless, inter and intra-institutional relationships do not always proceed in practice and the decision-making process is sometimes unilateral”*

4.3. Binational Cooperation

Historical treaties have been applied in relation to transboundary surface water along the Mexico-USA border (Wilder *et al*., 2020), such as the Guadalupe-Hidalgo Treaty in 1848, and La Mesilla Treaty in 1853 (IBWC, 1848; 1853). For the study area, the most important of these is the 1944 Treaty on the Utilization of Water of the Colorado and Tijuana Rivers and of the Rio Grande (Treaty). In that Treaty, 1,850 hm^3 per year of surface water were allocated from the Colorado River to Mexico. In order to operationalize compliance with the Treaty, specific agreements are signed, called Minutes. Some of the most relevant are described below.

4.3.1 Minute 242

The Minute 242 indicates several binational actions for a permanent and definitive solution to the international problem of the salinity in the Colorado River. The Minute also includes agreement on groundwater, by stating that “each country shall limit pumping of groundwater in its territory within eight kilometers of the Arizona-Sonora boundary, near San Luis, to 197.3 hm^3 per year.” To avoid future problems, “the USA and Mexico shall consult with each other prior to undertaking any new development of either the surface or groundwater resources or undertaking substantial modifications of present developments in its own territory in the border area that might adversely affect the other country”. (IBWC, 1973, pp.3).

However, this Minute was not considered in the lining of the All-American Canal project in 1998; the decision was a unilateral decision by the United States. Therefore, the recharge from the All-American Canal to the MVA was significantly reduced (CONAGUA, 2018b).

4.3.2. Minute 319

Minute 319 has a significant importance for the improvement of binational water management in the Colorado River. This Minute relates to at least three previously signed minutes: Minute 306, Minute 317, and Minute 318 (Sanchez & Cortez-Lara, 2015). Minute 319 was written following persistent dry conditions in the Colorado River Basin and the 2010 earthquake in the Mexicali Valley.

In addition, Minute 319 included protection of environmental flows of 195 hm^3 during the five-year term of the act, and the possibility of continued storage of water in dams upstream. This was the direct response of both countries to the issues raised by the April 2010 earthquake and its impact on the infrastructure of Irrigation District 014 in the Mexicali Valley (Sanchez & Cortez-Lara, 2015; Wilder *et al*., 2020).

Even though Minute 319 does not refer to groundwater, its implementation had a positive effect on the aquifer because of the environmental flows deliveries (designated water for the environment) to the Colorado River channel and restoration sites, where infiltrated water recharged the aquifer (IBWC, 2018; Rodríguez-Burgueño, 2017).

As an extension of these cooperative measurements, Minute 323 was created in 2017 to be implemented for a 7-year period.

4.4. Management Instruments

Several water management instruments are defined in the legal framework, particularly by the National Water Law; these are: National and States Hydraulic Programs, water concessions, pumping restrictions types, the Public Registry of Water Rights (REPDA), the integrated aquifer management plan, and the National Water Information System, the update of the annual average availability of groundwater per aquifer, among others.

4.4.1. National and States Hydraulic Programs

The strategies and line of actions for public policies to achieve the adequate governance of water resources has been captured in the National and States Hydraulic Programs. At the national scale, the main goal is to promote and to strengthen the governance and governability of water. The actions include sorting the use of water according to the priority established in the LAN, modernizing and expanding the measurement of the water cycle, increasing the social and academic participation in the decision-making process to decrease the conflict risk, and meeting the demands for information (SEMARNAT, 2014). These strategies are mostly aimed at the management, modernization, and improvement of water quality, but they have not been successful to date due to structural, operational, political, and economic factors, as well as the lack of systematic monitoring in the aquifers.

In the States Hydraulic Program, various projects and goals were established for the aquifers. One goal is the reduction of groundwater extraction from the MVA (which currently is 783 hm^3 per year) down to 456 hm^3 per year by 2035 (CEABC, 2018). In addition to the established strategies, emphasis is placed on the management of shared water resources, including transboundary aquifers. Management of these aquifers requires the creation of new international treaties and monitoring of the implementation of existing treaties.

However, these programs are updated in each government period so they are not given continuity to become established, and goals and strategies lack alignment with the management plans for the USA-portion of the aquifer, in the states of Arizona and California. For instance, the state of California, where a portion of the transboundary aquifer is located, has adopted a Sustainable Groundwater Management Act (SGMA) since 2014. This act emphasizes sustainable yield, which defines the maximum amount of groundwater that can be extracted without causing adverse effects. This amount is based on six indicators with the objective of evaluating the metrics defined in the Regulations for Groundwater Sustainable Plan (SGMA, 2014). Thus, the multi-jurisdictional and numerous asymmetries among the four states and two countries sharing the same aquifer prevent a truly international vision, cooperation, and management of the transboundary aquifer, of which the MVA is an important component.

4.4.2. Water Concessions

According to the National Water Law, water concessions represent the titles for exploitation and use of groundwater. To grant the concession, CONAGUA must consider the current condition of the aquifer in terms of available volume; in addition, the user must expressly indicate the conditions of variability of the water source from which the extraction will be carried out. The water concessions are valid for 5 to 30 years (LAN, 2020).

As stated by the National Water Law it is not possible to extract volumes of water that are greater than the authorized volumes in the concession. This condition is impossible to guarantee in the MVA wells because they do not have flow meters.

4.4.3. Public Registry of Water Rights

The registry provides information and legal security to users of national waters, including groundwater. It shows the name of the user, the type of use and the volume of water extracted, the location of the well, and the name of the aquifer. However, the information is not corroborated with measurements of the volumes of groundwater withdrawn from wells, so it does not accurately reflect actual information (Kuri, 2018).

4.4.4. Veda

The groundwater extractions in the MVA have been restricted since 1965. This restriction establishes that the capacity of the aquifer allows limited withdrawals for domestic, industrial, and other uses. It also indicates that no one may extract groundwater in the restricted area for pumping (zona vedada) or modify existing uses without prior written permission from CONAGUA, which only grants permission in those cases in which studies conclude that damages will not be caused (DOF, 1965).

Currently this decree is still in force, so in "theory" each of the wells that extracts water from the MVA has a volume granted by CONAGUA.

4.4.5. Integrated Management Plan of the Aquifer

In 2013, as part of a collaboration agreement between CONAGUA and the Mexican Institute of Water Technology (IMTA), the integrated Plan for the Mexicali and San Luis Rio Colorado Valleys aquifers was prepared. Unfortunately, the plan is not yet public, its contents are unknown, and it is not clear if it is already being applied.

05

Conclusions and Main Recommendations

This paper essentially discusses groundwater governance focused in the Mexicali Valley Aquifer (MVA), the Mexican-side of the much larger Lower Colorado River Basin Transboundary Aquifer (LCRB). Other transboundary aspects and effects of the full LCRB are currently under study separately, with a unified hydrogeological conceptual model, and are not discussed here.

The Mexican legal and institutional frameworks and existing instruments for management are reviewed within the Mexican perspective of groundwater governance. Existing binational instruments (Minutes) are briefly reviewed to evaluate the international context of groundwater-use practices along the border with the United States of America.

On the Mexican side, groundwater governance issues abound, mostly related to overexploitation of groundwater in the Mexicali Valley. Mexican laws and regulations on groundwater exist, but they cannot be complied due to the lack of aquifer monitoring and groundwater extractions measurements. Although the tasks of the principal Mexican water agency (CONAGUA) are well defined in the existing regulations, this federal agency does not have the financial and staff capacity to enforce the regulations entirely. A strategy that has worked partially to solve the lack of funds is collaborating with academic centers, such as the University of Baja California, using federal or other funding sources. Another strategy is creating the Technical Groundwater Council (COTAS) integrated into decision-making by water users of the MVA to contribute to the control and oversight of groundwater allocations, depletion, overexploitation, and monitoring; CONAGUA and other federal, state, or local government water agencies can guide technically.

“Sound shared groundwater resources management practices, associated with groundwater monitoring and shared governance, would go a long way to achieving water security for all jurisdictions”

The economy of the region heavily relies on aquifer management to maintain the sustainability of available water resources. Thus, a strong and continued commitment of research and government institutions and water users is desperately needed to reduce the aquifer’s adverse effects. In brief, political and economic issues impact the governance of the MVA and generate its overexploitation.

On the international side, binational cooperation has been possible thanks to the minutes prepared under the umbrella of the Water Treaty signed by the two countries in 1944: Minute 242 in 1973 and Minute 319 in 2012. For instance, in Minute 319, Mexico and the USA celebrated a cooperative approach of their “hydro-relations” on the Colorado River, highlighting the provision of water for the environment and hydraulic infrastructure. These events represent a great relief to groundwater users in the MVA, particularly for agricultural users and the environment. Although there are good examples of binational cooperation, they are not enough to solve the long-term situation of the MVA.

To solve the growing groundwater issues of the MVA and facilitate the decision-making process, Mexico needs to improve the inter and intra-institutional coordination to decrease the risk of conflicts regarding groundwater use in the MVA. In the case of the MVA, and given the multi-jurisdictional shared resource, it is necessary to create a new integrated plan with specific indicators and metrics which would consider the transboundary aquifer as a whole. Furthermore, additional funding is needed to support the creation of independent, modern groundwater monitoring systems in the study area and to increase technical and human capacity in local agencies and organizations.

Sound shared groundwater resources management practices, associated with groundwater monitoring and shared governance, would go a long way to achieving water security for all jurisdictions. In the case of the MVA, the scope of monitoring would require the periodic assessment of three primary parameters: water levels, pumping rates, and changes in water storage, to ensure compliance with the laws and define accurate water balances for well-informed aquifer-management decisions.

References

Ariel Construcciones, S. A. (1968). Complete hydrogeological study of the aquifers of the Valle de Mexicali, B.C and Mesa de San Luis, Son. [Estudio hidrogeológico completo de los acuíferos del Valle de Mexicali, B.C y Mesa de San Luis, Son.].

Caballero, G. A. (2014). Local units of managing of the Mexicali Valley transboundary aquifer [Unidades locales de gestión del acuífero transfronterizo del Valle de Mexicali] (Master thesis). https://doi.org/10.1017/CBO9781107415324.004.

Cázares, Z. M. (2008). Geohydrological And Legal Considerations In The Management Of Ground Water In The Valley Of Mexicali, Baja California, Before The Lining Of The All-American Channel [Consideraciones Geohidrológicas y Legales en la Gestión del Agua Subterránea del Valle de. https://www.colef.mx/posgrado/tesis/2006725/.

CEABC. (2018). Baja California Vision 2035 Water Program [Programa Hídrico del Estado de Baja California Visión 2035] (pp. 1–114). State Water Commission. http://www.cea.gob.mx/phebc/resejec/RESUMEN EJECUTIVO PHEBC.pdf.

______. (2020). State Water Commission. About Us. http://www.cea.gob.mx/organismo.html.

CESPM. (2020). Mexicali State Commission of Public Services. About Us. http://www.cespm.gob.mx/tf-nosotros.html#gsc.tab=0.

Chen, J., Wu, H., Qian, H. & Li, X. (2016). Challenges and prospects of sustainable groundwater management in an agricultural plain along the Silk Road Economic Belt, north-west China. *International Journal of Water Resources Development*, 34(3), pp. 354–368. https://doi.org/10.1080/07900627.2016.1238348.

Cital, F., Rivera, A., Rodriguez Burgueño, E. L., Ramírez-Hernández, J. & Carreon, C. (2021). A unified hydrogeological conceptual model of the Lower Colorado River Basin transboundary aquifer, traversing the US/Mexico international border; *in preparation*.

CONAGUA. (2007). Agreement by which the annual average availability of groundwater of the 653 aquifers of the United States is update, which are part of the hydrological-administrative regions indicated.

______. (2009). Agreement by which the geographical location of 371 aquifers in the national territory is disclosed, it is update the average annual availability of groundwater from 282 aquifers, and modifies for better precision, the geographic description of 202 aquifers.

______. (2010). Agreement by which the annual average availability of groundwater of the 653 aquifers of the United States is update, which are part of the hydrological-administrative regions indicated.

______. (2013). Agreement by which the annual average availability of groundwater of the 653 aquifers of the United States is update, which are part of the hydrological-administrative regions indicated.

______. (2014). Number of users, surface with irrigation rights and volume assigned by source of supply. Agricultural Cycle 2014-2015. National Water Commission.

______. (2015a). Update of the mean annual water availability Valle de Mexicali (0210), Baja California State [Actualización de la disponibilidad media anual de agua Valle de Mexicali (0210), Estado de Baja California].

______. (2015b). Groundwater regulations and Irrigation District. Vectorial data. https://datos.gob.mx/busca/dataset?tags=mapa. https://www.gob.mx/cms/uploads/attachment/file/103411/DR_0210.pdf.

______. (2018a). Agreement by which the annual average availability of groundwater of the 653 aquifers of the United States is update, which are part of the hydrological-administrative regions indicated.

______. (2018b). Resultados obtenidos en los levantamientos piezométricos en acuíferos que cuentan con red de monitoreo en Baja California. Comisión Nacional del Agua.

______. (2018c). Statistics on water in Mexico 2018 Edition [Estadísticas del Agua en México Edición 2018].

______. (2020). Agreement by which the annual average availability of groundwater of the 653 aquifers of the United States is update, which are part of the hydrological-administrative regions indicated.

Constantino, R., Carrillo, G., Muñoz, C. & Morales, E. (2011). Eficiencia en el uso de los recursos en América Latina: Perspectivas e implicancias económicas. In La situación de los recursos hídricos en México y el contexto institucional de la eficiencia en su aprovechamiento. http://wedocs.unep.org/bitstream/handle/20.500.11822/9106/-Eficiencia en el uso de los recursos en América Latina-2011REEO WEB FINAL.pdf?sequence=3&isAllowed=y.

Constitución Política de los Estados Unidos Mexicanos. (1917). Articulo 115. Constitución Publicada en el Diario Oficial de la Federación el 5 de febrero de 2017. Ultima reforma DOF 08-05-2020.

Cortez-Lara, Andrés. (1999). Dynamics and conflict over the transboundary waters of the Colorado River: the All-American Canal project and the hydraulic society of the Mexicali Valley [Dinámicas y conflicto por las aguas transfronterizas del Río Colorado: el proyecto All-American Can. Revista Frontera Norte, El Colegio de La Frontera, BC., …, 11(21), pp. 33–60. http://www2.colef.mx/FronteraNorte/articulos/FN21/2-f21_Dinamica_y_conflicto_aguas_transfronterizas_rio_colorado.pdf.

Dell'Angelo, J., Rulli, M. C. & D'Odorico, P. (2018). The Global Water Grabbing Syndrome. *Ecological Economics*, 143, pp. 276–285. https://doi.org/10.1016/j.ecolecon.2017.06.033.

Díaz, P. (2001). Numerical simulation of the upper aquifer of the Mexicali Valley, Baja California, México [Simulación numérica del acuífero superior del Valle de Mexicali, Baja California, México] (Master thesis). https://cicese.repositorioinstitucional.mx/jspui/handle/1007/2388.

DOF. (1965). Decreto por el que se establece la veda para el alumbramiento de aguas del subsuelo en el Estado de Baja California. Diario Oficial de la Federación. http://www.dof.gob.mx/nota_to_imagen_fs.php?codnota=4616319&fecha=15/05/1965&cod_diario=198386.

______. (2018). Acuerdo por el que se actualiza la disponibilidad media anual de agua subterránea de los 653 acuíferos de los Estados Unidos Mexicanos, mismos que forman parte de las Regiones Hidrológico-Administrativas que se indican. Diario Oficial de la Federación. http://www.dof.gob.mx/nota_detalle.php?codigo=5510042&fecha=04/01/2018.

Famiglietti, J. S. (2014). The global groundwater crisis. *Nature Climate Change*, 4(11), pp. 945–948. https://doi.org/10.1038/nclimate2425.

FAO. (2016a). Global Framework for Action to achieve the Vision on Groundwater Governance. http://www.fao.org/3/a-i5705e.pdf.

______. (2016b). Shared global vision for Groundwater Governance 2030 and Call-for action (pp. 1–19). Food and Agriculture Organization. http://www.fao.org/3/a-i5508e.pdf.

Feirstein, E. J., Zamora, F., Vionnet, L. B. & Maddock III, T. (2008). Simulation of groundwater conditions in the Colorado River Delta, Mexico (Master thesis). http://hdl.handle.net/10150/615772%09.

Foster, S. & Garduño, H. (2013). Gouvernance de la ressource en eau souterraine: Gouvernements et acteurs répondent-ils au défi? *Hydrogeology Journal*, 21(2), pp. 317–320. https://doi.org/10.1007/s10040-012-0904-9.

Foster, S., Garduño, H. & Kemper, K. (2004). The "COTAS": Progress with stakeholder participation in groundwater management in Guanajuato-Mexico. GW-MATE Case Profile, 10.

Gleeson, T., Wada, Y., Bierkens, M. F. P. & van Beek, L. P. H. (2012). Water balance of global aquifers revealed by groundwater footprint. *Nature*, 488(7410), pp. 197–200. https://doi.org/10.1038/nature11295.

GWP (Global Water Partnership) & INBO (International Network of Basin Organizations). (2009). Manual for the integrated management of water resources in basins [Manual para la gestión integrada de recursos hídricos en cuencas]. https://www.rioc.org/IMG/pdf/RIOC_GWP_Manual_para_la_gestion_integrada.pdf.

GobMex. (2014). Gobierno de México. CILA MEX-EUA. https://www.gob.mx/sre/acciones-y-programas/c-i-l-a-mex-eua.

IBWC. (1848). Treaty of Peace, Friendship, Limits and Final Settlement between the United Mexican States and the United States of America.

______. (1853). Boundary Treaty between the United Mexican States and the United States of America.

______. (1973). Minute No. 242 Permanent and Definitive Solution to the International Problem of the Salinity of the Colorado River (pp. 1–4). International Boundary and Water Commission (IBWC). https://www.ibwc.gov/Files/Minutes/Min242.pdf.

______. (2018). Minute 319 Colorado River Limitrophe and Delta Environmental Flows Monitoring Final Report. https://www.ibwc.gov/Files/Minute_319_Monitoring_Report_112818_FINAL.pdf.

Kuri, G. H. (2018). Groundwater in Mexico: challenges and pending for the transformation of its management [Agua subterránea en México: retos y pendientes para la transformación de su gestión]. In C. Denzin, F. Taboada & R. Pacheco-Vega. (eds.) *El agua en México. Actores, sectores y paradigmas para una transformación social-ecológica*, Issue April, pp. 149–170. https://agua.org.mx/wp-content/uploads/2018/04/El-agua-en-Mexico.pdf.

LAN. (2020). National Water Law [Ley de Aguas Nacionales] (pp. 1–91). Cámara de Diputados del H. Congreso de la Unión. http://www.diputados.gob.mx/LeyesBiblio/pdf/16_060120.pdf.

Margat, J. & van der Gun, J. (2013). Groundwater around the world. A Geographic Sypnosis (J. Margat & J. van der Gun, Eds.; Issue 2). CRC Press.

Murillo-Licea, D. & Soares-Moraes, D. (2013). The pendulum of governance and water governance in Mexico [El péndulo de la gobernabilidad y la gobernanza del agua en México]. *Tecnología y Ciencias Del Agua*, 4(3), pp. 149–163.

Nair, K. S. (2016). Impact of climate change and anthropogenic pressure on the water resources of India: challenges in management. *Proceedings of the International Association Og Hydrological Sciences*, 374, pp. 63–67. https://doi.org/10.5194/piahs-374-63-2016.

Olmsted, F. H., Loeltz, O. J. & Irelan, B. (1975). Geohydrology of the Yuma Area, Arizona, and California. U.S. Geological Survey Professional Paper 486-H, 1–227.

Periódico Oficial del Estado de Baja California. (2020). Decree No. 67. https://wsextbc.ebajacalifornia.gob.mx/CdnBc/api/Imagenes ObtenerImagenDeSistema?sistemaSolicitante=PeriodicoOficial/2020/Mayo&nombreArchivo=Periodico-25-CXXVII-2020512-NÚMERO ESPECIAL.pdf&descargar=false.

Ramírez-Hernández, J. (2020). Transboundary groundwater in the Colorado River Delta, a challenge for collaboration [Las aguas subterráneas transfronterizas del Delta del Río Colorado, un reto para la colaboración]. In Alfonso Cortez-Lara & Castro, J. L. (eds.) *Visiones contemporáneas de la cooperación y la gestión del agua en la frontera México-Estados Unidos*.

REPDA. (2018). Public Registry of Water Rights [Registro Público de Derechos de Agua (REPDA)]. National Water Titles and Permits and Their Inherent Public Assets. https://app.conagua.gob.mx/Repda.aspx.

Richey, A. S., Thomas, B. F., Lo, M.-Hu., Famiglietti, J. S., Swenson, Sean. & Rodell, M. (2015). Uncertainty in global groundwater storage estimates in a Total Groundwater Stress framework. *Water Resources Research*, 51, pp. 5198–5216. https://doi.org/ https://doi.org/10.1002/2015WR017351.

Rivera, A. (2007). Groundwater Indicators: A Proposal For Regional-Scale Aquifers. IAH OttawaGeo2007/OttawaGéo2007, 1–8.

Rodriguez-Burgueño, J. E. (2012). Transient geohydrological modeling of the aquifer-river relationship of the FFCC-Carranza ford of the Colorado River for the management of the riparian zone [Modelación geohidrológica transitoria de la relación acuífero-río de la zona FFCC-vado Carranzad].

______. (2017). Hydrological effects of pulse and base flows in the riparian zone of the Colorado River Delta [Efectos hidrológicos de los flujos pulso y base en la zona riparia del Delta del Río Colorado] (Doctoral dissertation).

Sanchez, V. & Cortez-Lara, A. A. (2015). Minute 319 of the International Boundary and Water Commission between the US and Mexico: Colorado River binational water management implications. *International Journal of Water Resources Development*, 31(1), pp. 17–27. https://doi.org/10.1080/07900627.2014.922465.

Sanchez, R. & Eckstein, G. (2017). Aquifers shared between Mexico and the United States: Management perspectives and their transboundary nature. *Groundwater*, 55(4), pp. 495-505.

SEMARNAT. (2014). Hydric National Program 2014-2018 [Programa Nacional Hídrico 2014-2018] (Issue 1). http://www.conagua.gob.mx/conagua07/contenido/documentos/PNH2014-2018.pdf.

______. (2010). Basic documents of Basin Councils. Secretaria del Medio Ambiente y Recursos Naturales. México.

SEMARNAT & IMTA. (2020). Water in the Mexicali Valley, Baja California: Origin, use and destination [El Agua en el Valle de Mexicali, Baja California: Origen, uso y destino] (pp. 1–37). Secretary of Environment and Natural Resources and Mexican Institute of Water Technology. https://aguaparatodos.org.mx/archivosapt/120c.pdf.

SGMA. (2014). Sustainable Groundwater Management Act. California Water Code. State of California. http://groundwater.ucdavis.edu/SGMA/%0Awww.downeybrand.com

Shah, T., Molden, D., Sakthivadivel, R. & Seckler, D. (2001). Global Groundwater Situation: Opportunities and Challenges. *Economic and Political Weekly*, 36(43), pp. 4142–4150. https://www.jstor.org/stable/4411304.

UNESCO. (2012). United Nations Educational, Scientific and Cultural Organization. The World's Groundwater Resources Are Suffering from the Effects of Insufficient Governance, Experts Say. http://www.unesco.org/new/en/media-services/single-view-tv-release/news/los_recursos_de_agua_subterranea_del_mundo_estan_sufriendo/.

______. (2015). Regional Strategy for the Assessment and Management of the Transboundary Aquifer Systems in the Americas. In PHI-VIII/SERIE ISARM AMÉRICAS No 4 (Issue Serie ISARM Americas, No.4). UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000235394.

Villholt, K. & Conti, K. (2018). Groundwater governance: rationale definition, current state and heuristic framework. In Villoholth, K., López-Gunn, E., Conti, K., Garrido, A. & van der Gun, J. (eds.) *Advances in Groundwater Governance,* pp. 3–32. CRC Press/Balkema. https://www.un-igrac.org/sites/default/files/resources/files/advances-in-groundwater-governance.pdf.

Vrba, J. & van der Gun, J. (2004). The world's groundwater resources. Contribution to Chapter 4 of WWDR-2. Igrac, 2(December), 1–10. https://www.un-igrac.org/sites/default/files/resources/files/Rapport 3 - groundwater resources.pdf.

Weiskel, P. K., Vogel, R. M., Steeves, P. A., Zarriello, P. J., DeSimone, L. A. & Ries, K. G. (2007). Water use regimes: Characterizing direct human interaction with hydrologic systems. *Water Resources Research*, 43(4), pp. 1–11. https://doi.org/10.1029/2006WR005062.

Wester, P., Hoogesteger, J. & Vincent, L. (2009). Local IWRM organizations for groundwater regulation: The experiences of the Aquifer Management Councils (COTAS) in Guanajuato, Mexico. In Natural Resources Forum (Vol. 33, No. 1, pp. 29-38). Oxford, UK: Blackwell Publishing Ltd.

Wester, P., Minero, R. S. & Hoogesteger, J. (2011). Assessment of the development of aquifer management councils (COTAS) for sustainable groundwater management in Guanajuato, Mexico. *Hydrogeology Journal*, 19(4), pp. 889-899.

Wilder, M. O., Varady, R. G., Gerlak, A. K., Mumme, S. P., Flessa, K. W., Zuniga-Teran, A. A., Scott, C. A., Pablos, N. P. & Megdal, S. B. (2020). Hydrodiplomacy and adaptive governance at the U.S.-Mexico border: 75 years of tradition and innovation in transboundary water management. *Environmental Science and Policy*, 112(January), pp. 189–202. https://doi.org/10.1016/j.envsci.2020.05.013.

World Economic Forum. (2019). Global Risks Report 2019. In Global Risk Report. http://www3.weforum.org/docs/WEF_Global_Risks_Report_2019.pdf.

10

Switching from Stock to Flow to Achieve Water Security: the Case of Palestine

Julie Trottier and David B. Brooks

Julie Trottier, Centre National de la Recherche Scientifique, France.
e-mail: Julie.TROTTIER@cnrs.fr
David B. Brooks, International Institute for Sustainable Development, Canada.
e-mail: david.b.brooks34@gmail.com

Abstract

This paper proposes to switch from a water stock to a water flow paradigm and therefore elaborate a new definition of water security. When seen and analyzed as a flow, it becomes possible to treat water as a substance with which a great variety of actors interact over a great variety of scalar levels. The paper also proposes a methodology to explore water security according to this new definition. The spatial, institutional, and sectoral trajectories that water follows both above and below ground are emphasized from the point where it emerges to the point where it disappears. After a brief review of existing governance systems in Israel and the West Bank, water security is analyzed in three Palestinian case studies: wells and springs in Al Far'a Valley; wastewater reuse; and irrigation in the Jordan River basin. Whereas past negotiations between Israeli and Palestinian authorities have focused on securing a stock of water, this paper concludes that reformulation of water security in terms of flows of water will open broader possibilities for forms of water governance that will promote sharing of transboundary water and ensure water security for all parties.

Keywords

Water security, water governance, Palestinian water management, wastewater reuse, water trajectories approach, irrigation water security

01
Water Governance

1.1. Water Governance

Approaches of water governance have mostly been normative and have focused on "good governance" as a set of institutional arrangements deemed desirable to manage water (FAO, forthcoming). Typically, examples of such studies focus on the need for transparency (Floress *et al.*, 2019). Recently, the FAO has chosen a more analytical approach to the concept of governance and has defined it as "the formal and informal rules, organizations, and processes through which public and private actors articulate their interests; frame and prioritize issues; and make, implement, monitor, and enforce decisions" (FAO, forthcoming). Throughout this article, the term "water governance" corresponds to this second definition, which proves useful because it recognizes that water management is historically constructed within a specific geographic, political, economic, and cultural context. It is also useful because it recognizes that many actors exercise social control over water over many scalar levels that sometimes overlap.

1.2 Some Existing Definitions of Water Security

The term "water security" is even more polysemic. When reviewing 95 articles compiled in 2010, Cook and Bakker noted the diversity of disciplines each of which deploys distinct framings and methodologies when approaching the concept of water security (Cook & Bakker, 2012). They also observed that each discipline tended to focus on a different scale. Development studies tended to focus on a national scale, hydrologists focused on the watershed scale, while social scientists preferred the community scale. They also noted that framings of water security depended on the perspective prevailing within a discipline; for example:

- Legal scholars considered water security was linked to allocation rules
- Agricultural scholars linked it to protection from drought and flood risk.

While the 1990s had produced definitions of water security that were linked to human security issues, such as military, food, or environmental security, the Second World Water Forum in The Hague in 2000 saw the Global Water Partnership introduce a more integrated definition of water security that included access and affordability of water as well as human needs and ecological health (Cook & Bakker, 2012). In their conclusion, the authors argued in favour of a broad framing of water security because they considered it complementary with Integrated Water Resources Management and because it brought water governance to the fore and was therefore more analytically robust. Water security, they said, was an overarching conceptual framework that insists on the need to balance competing land and water use practices. However, they added, in order to become operational, it needed to be narrowed and assessed over multiple scales, not only over national scales.

Malekian *et al.* (2017) later examined the various definitions and approaches of water security by linking them to paradigms instead of disciplines. They defined a paradigm as a set of assumptions, concepts, values, and practices that constitute a way of viewing reality for the community that shares them. They selected three paradigms: positivism, constructivism, and critical theory. They then proceeded to explore the definition of security provided by each paradigm, the definition of water security and that of agricultural water security, as well as the research objectives, tools, methods, and outcomes that emerge from each paradigm. Within a positivist paradigm, they argued, water security is an objective reality that can be measured by indices such as the volume of renewable water per capita within a state, concentration of dissolved oxygen in water, water consumption per $10,000 GDP, etc. Within a constructivist paradigm, an issue becomes a security issue once it is labelled as such. Water security is thus a complex problem because many actors with different backgrounds, interests, and opportunities co-exist and "securitize" water differently. Within a critical theory paradigm, water security refers to unshackling the barriers to inclusion and communication and refraining from barring others from also exercising their rights (Malekian *et al.*, 2017).

Malekian *et al.* (2017) showed that agricultural water security is explained, within a positivist paradigm, in terms of facts that are obtained by eliminating context factors. For example, water availability per capita expressed total water availability within a state, and water withdrawal per capita showed the control a state had over its water. Within a positivist paradigm, the authors argued, research objectives consisted of measuring water security at the international or national level and identifying threats to it. The research tools favoured within such a paradigm are questionnaires, surveys, and measurements to collect numerical, measurable data. The positivist paradigm usually promotes deductive research processes that provide results claiming to represent the "real" situation through the generation of numerical data and information.

Paradigms may be shared across disciplines. Natural sciences favour to this day the positivist paradigm when defining and exploring water security. For instance, Vörösmarty *et al.* (2018) argue in favour of linking an ecosystem-based water security concept to the Sustainable Development Goals (SDGs) through a strictly positivist paradigm that perceives unruly human interactions with water as needing to be disciplined by states. Crucially, though, such authors may find collaborators from social sciences sharing their paradigm. Their attempts at interdisciplinary studies of water security will thus never challenge the paradigm most natural scientists adhere to. This practice contributes greatly to explaining the poor integration of social sciences within interdisciplinary studies of water (Fustec and Trottier, 2016). Indeed, when elaborating research questions, social scientists usually challenge the paradigm that produced the questions.

Malekian *et al.* (2017) argue that, within a constructivist paradigm, agricultural water security is inter-subjective, constituted by a process of interaction and negotiation inherited from cultures, traditions and institutions.
To them, agricultural water security is a dynamic concept, the interpretation of which may vary among farmers, even among neighbours going through similar situations. Interpretations will vary according to what is perceived as secure in terms of water quantity and quality. The research tools favoured within a constructivist paradigm are in-depth interviews, focus groups and narrative analysis. This paradigm favours inductive processes to formulate hypotheses. However, within a critical theory paradigm agricultural water security means securing vulnerable farmers from the structural violence limiting adequate water supply for sustainable agriculture while ensuring others are not deprived and the environment is not degraded. In other words, within a critical theory paradigm, agricultural water security means freeing farmers from structures of power preventing them from living as they wish. This paradigm favours the tools of research-action.
The concept of structural violence is fundamental in critical theory. It was coined by Galtung when he distinguished direct, structural, and cultural violence. Galtung (1969) defined structural violence as the set of -- mostly economic, but also socio-political – processes that prevent an individual or a group from achieving its full potential.

Malekian *et al.* (2017) conclude that “Each paradigm results in a specific logic and framing of acceptable water security in the agricultural sector, including who can and should determine it, and how it can be assessed.” Crucially, the authors note that these paradigms are complementary. They need not be and seldom are mutually exclusive.

Changing Definitions of Security from a Focus on Stocks to a Focus on Flows

As shown above, literature on water security has systematically referred to quantity and quality of water. It has rarely referred to flows of water. Yet, all water flows, including most ground water. Only a small portion, generally called fossil ground water, is held between nearly or completely impermeable layers of rock and is either unable to move at all or moves very slowly. Throughout, water security studies have treated water as an annually renewable stock, even when they discussed flood risks. We define this as the water stock paradigm. We propose to switch to a water flow paradigm to reexamine the issue of water security. In other words, we propose to treat water first and foremost as a flow with which a great variety of actors interact over a great variety of scalar levels.

02

A Definition of Water Security Based on Flows

We propose a definition of water security and a methodology that allows us to benefit from the complementary use of different paradigms. Forsyth (2003) shows how realist, relativist, or constructivist paradigms lead to different understandings of the scientific depiction of the “universal” soil loss equation. Malekian *et al.* (2017) demonstrate how positivist, constructivist, or critical theory paradigms lead to different understandings of water security. A useful definition of water security must allow us to explore this topic within any paradigm.

Similarly, a useful definition of water security should not trap us in a narrow disciplinary understanding that would dictate the scales at which the topic needs to be investigated or the hypotheses that can be formulated. Disciplinary boundaries are not helpful for research; they are only helpful for researchers’ careers.

Consequently, we propose to focus on flow rather than stock when putting forward a definition of water security. This is important for five main reasons:

1) A water flow links all the actors who interact with it. Following this flow will allow identifying these actors in an inductive fashion, including those who lose when the flows are redirected from one trajectory to another via a development project, for instance. This frees us from the narrow hypotheses deployed within individual disciplines.
2) Water flow links actors who deploy their strategies over various scalar levels. Following a water flow thus frees us from the pre-determined scale of analysis that each discipline privileges. For instance, as Malekian *et al.* (2017) detailed, disciplines deploying a positivist paradigm privilege the national scale. Yet, most actors, such as farmers, deploy their strategies over a much smaller scale.
3) Climate change affects flows as much as it affects water stocks. However, because we use flows as a heuristic tool through the spatial, institutional, and sectoral trajectories that water follows, the fact that climate change affects flows does not disrupt the analysis of water security as much as it affects the analysis of water stocks.
4) When a development project or any form of infrastructure reduces or suppresses the flow along one trajectory to direct its water along a new trajectory, such as happens, for instance whenever a treated wastewater reuse project is carried out, focusing on the flow of water before and after the project allows identifying many actors currently made invisible by the present water stock paradigm.
5) Each of flow or stock may prove to be the limiting variable, i.e., the predominant constraint, within a human-made system. However, indicators treating water as stock do not consider the manner flow may also prove to be a limiting

variable. This is the case, for instance with the water scarcity indicators that combine a water stress index with a water shortage index (as with Falkenmark *et al.*, 2007; Falkenmark & Molden, 2008).

We therefore propose the following definition of water security:

Water security is achieved when water governance over all scalar levels ensures an interaction with the flow of water that is consensually considered equitable across all social groups, including vulnerable minorities, while also ensuring the long-term sustainability of the environment.

> *“Water security is achieved when water governance over all scalar levels ensures an interaction with the flow of water that is consensually considered equitable across all social groups”*

Crucially, the word “equitable” here does not mean that every actor will necessarily be able to interact with the flow of water as he or she wishes. The case study we investigate here lies in a semi-arid region. Clearly, many farmers could produce more if they could access more water, i.e. if they could interact with the flow of water to increase the consumptive part of their use of that flow. They do not achieve the full potential that they consider their land could reach because they do not have access to irrigation water. We argue that such structural violence is unavoidable when looking at water governance in a semi-arid environment, which is the most difficult climatic region for water management (Bakour & Kolars, 1994). In contrast to more temperate regions, water managers have to plan for extremes of weather rather than averages. However, governance that is considered equitable is possible. In such a case, all actors agree that the manner they interact with the flow of water is legitimate and just. Forms of water governance that prove to be resilient in the face of climate, economic, or demographic change have been shown to be considered equitable among the people that deployed them (Mabry, 1996; Trawick, 2002; Boelens, 2015).

03
Key Questions Addressed

Cook and Bakker (2012) argued that a definition of water security needs to be narrowed in order to become operational even though a broad definition was more analytically robust. There is much to be said for the argument that a narrow definition helps implementation, as indicated in the recent IWRA policy brief on water security and the sustainable development goals (IWRA, 2020). However, our paper argues in favour of a broad definition of water security that becomes operational because it focuses on water flow instead of water stock. First, we detail the methodology to investigate water security by focusing on the trajectories water flows along. Second, we apply this methodology to show how it reveals the degradation of water security for many actors who are currently made invisible by the hegemonic water stock paradigm. In particular, this methodology produces a different picture of water security from that which emerges from either the academic literature or policy documents concerning the West Bank and Palestinian institutions responsible for managing water. Third, as part of the case study, we look at three specific aspects of West Bank water: (1) the interaction between wells and springs in Al Far’a Valley, (2) wastewater reuse, and (3) irrigation in the Jordan Valley.

In many ways, the emphasis on trajectories in this paper extends recent work on de-securitization of fresh water in the region (Fischhendler, 2015; Kronich & Maghen, 2020; Brooks & Trottier, 2014). The several forms of trajectories show what changes when water is no longer treated as a security issue “that must be protected” but rather becomes subject to changes in governmental policies or private actions for managing water as an economic resource.

04
Methodology

We began our work by identifying the spatial, institutional, and sectoral trajectories of water flows in the West Bank. The spatial trajectory of water refers to the paths it travels both above ground and underground. The institutional trajectory of water refers to the successive human institutions managing it from the moment it emerges from the earth, or from a desalination plant, to the point where it evaporates, is transpired by a plant or an animal, or reaches the sea or a deep aquifer. In the case of water that is retained by a plant, the last institution involved in this trajectory is the institution that managed the water as it was entering the plant. The sectoral trajectory of water refers to the successive sectors of activity, such as agriculture or industry, that use a water flow. Each of these types of trajectory and the manner they can be altered either naturally or through the construction of infrastructure has been described elsewhere (Trottier *et al.*, 2019).

Analyzing water security using the water trajectories approach required us to take three specific steps:

1) We identified, along every water trajectory, the actors who were interacting with the flow. We identified the use they made of water and the manner they affected the quality of the water that kept on flowing along the spatial trajectory, as well as any consumption of water from their interaction. We identified the institutions they resorted to for regulating their interaction with water as well as the scale over which each institution extended its regulation. We also identified the scale over which this actor deployed his or her activity. Along the same spatial trajectory, or the same water flow, we identified actors who resorted to different institutions and deployed their actions over a great variety of scalar levels. All of these were explored because they contribute to constructing or eroding water security.

2) We investigated land and water tenure along the full spatial trajectory of water as well as the land and water tenure deployed by every actor interacting with the water flow. Water and land tenure are respectively the relationship, whether legally or customarily defined, between people, as individuals or groups, with respect to water resources and land resources (Hodgson, 2016). Exploring how both land and water tenure functions is crucial because irrigation, which is located at the interface of these two forms of tenure, makes up 70% of the consumptive use of water around the world, and even 80% in some Middle Eastern countries (Beaumont, 2002). Exploring tenure is crucial because it allows a much deeper understanding of the sources of legitimacy concerning water access, water use and water allocation. Tenure is often constructed on the basis of legal pluralism. This means that several sources of authority may produce norms that are sometimes conflicting yet apply over the same space. Actors will call upon a norm and a source of authority in a given instance and will call upon other norms and other sources of authority in other instances (Bruns & Meinzen-Dick, 2001). The FAO now recognizes the importance of considering water tenure and is producing a guide to assess it (FAO, 2020).

3) We identified "unwitting water uses" and unwitting negative impacts on water. For example, we identified the role of leaks in local food security. A local variety of mallow called Khubbezeh is especially nourishing. It is a weed and proliferates when irrigation systems leak. Local custom allows anyone to secure permission from the farmer to pick it free of charge. This helps the farmer because it means his field is weeded, and it ensures local food security. This "unwitting water use" plays a crucial role in food security. Linking food and water security has often been described as very difficult (Falkenmark, 2001). Following the trajectory of water helps us overcome such difficulty. Conversely, we also identified unwitting negative impacts on water, such as that of urban development. For example, when impermeable surfaces increase, the recharge of springs and wells can be reduced. Such a phenomenon was observed when surrounding settler and Israeli urban development reduced the flow of the springs in Wadi Fukin (Haviv & Asaf, 2005).

05

Case Study Synopsis

We use the West Bank in Palestine as a case study in order to illustrate the usefulness of approaching water security as a flow. The field work for this research was carried out from January 2013 until August 2018 thanks to two projects. The project Of Lands and Waters was funded by the Agence National de la Recherche Scientifique from January 2013 until December 2017. The project The Paracommons of Palestinian Water is funded by the Agence Française de Développement since November 2016 and will last until June 2021.
These two projects allowed Julie Trottier to carry out 5 years and 7 months of field work in the West Bank. It also allowed Jeanne Perrier to carry out 11 months of field work in the West Bank and provided the basis for her Ph.D. dissertation.

Water security in the West Bank is usually conceived by researchers in terms of national endowments of water for either Israelis or Palestinians (Aggestam, 2015; Feitelson *et al.*, 2012) and by policymakers in terms of securing water supply and sanitation for the population (World Bank, 2018). This is linked to the specific history of the West Bank. Israel and the West Bank were once part of the British Mandate over Palestine until the 1949 armistice. While Israel then became a state in 1948, the West Bank was annexed by Transjordan which then became Jordan. The interim border between Israel and the West Bank, known as "the Green Line" because of the color used on maps, was nothing more than the armistice line. In 1967, Israel occupied the West Bank but, to now, has not annexed it. Subsequently, Jordan relinquished all authority over the West Bank in 1988, and the Oslo agreements were concluded as a set of three treaties in 1993, 1994 and 1995. These treaties allowed a mutual recognition of Israel and the Palestinian Authority during an interim period that was supposed to last until 1999. A final status agreement was then supposed to settle permanently the most thorny issues: the fate of Palestinian refugees, the capital of the future Palestinian state, national borders, water, and the fate of Israeli settlements in the West Bank and Gaza Strip. Most observers now accept that it was an error to leave all those issues to the end; it meant that nothing could be resolved until everything was resolved (Sher, 2018), In particular, we have composed a draft water agreement on fresh water that could be concluded in advance of other issues (Brooks & Trottier, 2012) and more recently published a short "opinion" article entitled Moving Water from Last to First in the Middle East Peace Process (Brooks & Trottier, 2020). This final status agreement has not yet been concluded, and Israeli occupation of the West Bank continues.

5.1. National and Local Water Management

Under the British Mandate, water had always been managed locally, usually through grassroots common property regimes designed to manage springs and wells used both for domestic water and for irrigation. When Israel became an independent state, it rapidly centralized water management at the national level while decentralized, locally elaborated water management persisted in the West Bank (Trottier, 1999; 2007). Article 7, paragraph 4 of the Declaration of Principles of 13 September 2013, the first of the three treaties that make up the Oslo Agreements, announced the creation of the Palestinian Water Authority (PWA) (Trottier, 1999, p. 63).
Later, Annex II of the Cairo Agreement of 4 May 1994, the second of the three treaties that make up the Oslo Agreements, detailed in its article II, section B, paragraph 31 that it entrusted the PWA with managing all of the water attributed to the Palestinians, including sewage (Trottier, 1999, p.65). The agreement signed in Washington on 28 September 1995, the third of the three treaties that make up the Oslo Agreements specified quantities of water attributed to Israelis, on one hand, and to Palestinians, on the other hand, from each of the three main aquifers of the West Bank (see Map 10-1) in its Annex 10, paragraph 20, article 40 of the Protocol Concerning Civil Affairs (Trottier, 1999, p.66).
This agreement treated water strictly as a stock. Researchers and policy makers followed suit and mostly treated water security in the West Bank as an issue of allocating a sufficient quantity of water to the Palestinians.

5.2. Donor supported Water Projects in the West Bank

Since 1994, the West Bank became the object of over 2,000 donor-supported water development projects aiming to assist the Palestinian Water Authority (Trottier *et al.*, 2019). International donors considered the Palestinian water law, first promulgated in 2002, and the Oslo agreements as the legal basis for their projects. They largely neglected the grassroots institutions that persisted in managing surface and ground water at the local level throughout the West Bank for agriculture purposes. Donor-funded projects were studied in depth (Trottier *et al.*, 2019) The results show that by 2009, less than 1% of the water projects were targeted at agricultural water. By 2016, this figure had risen to a little below 10%.
All of the domestic water and waste water projects, i.e. over 90% of the projects, were funded through the PWA to increase its capacity to manage water and treat waste water. The rare projects that targeted agricultural water were funded either through the Ministry of Agriculture, the PWA or non-governmental organisations. None channeled funds to the grassroots, often informal institutions that managed surface and ground water at the local level even though these institutions manage most of the water consumed by Palestinians. The focus on overall quantities of renewable water within Israel and the West Bank, as occurred within the Oslo agreements, led to groundwater management planning

that remained unimplementable and unimplemented because it didn't integrate the interactions that many local actors, mostly farmers and farmer organizations, maintained with surface and ground water. The result now is unsustainable abstraction of ground water, which has led to the disappearance of many essential springs while paradoxically fueling interstitial Palestinian agricultural frontiers in the West Bank (Trottier & Perrier, 2018).

5.3. Israeli Settlements and the Occupation of the West Bank

The issue of Israeli settlements and the persistent Israeli occupation in the West Bank constitutes a difficulty for the application of our water trajectory approach in order to assess water security as per our definition. Israeli settlers have curtailed Palestinian use of many springs (Braverman, 2019). Mekorot, the Israeli national water company, drilled wells in the West Bank that sometimes dried out neighboring springs used by Palestinian farmers (Trottier, 2015).
Such actors are readily identified when applying the water trajectory approach. But their interaction with the flow of water cannot be considered equitable because of the nature of settlements and their lack of legal standing in international law (Brooks *et al.*, 2020). However, applying the water trajectory approach to the West Bank allows us to identify far more thorns to water security than the role played by settlements and occupation authorities in the West Bank.

5.4. The Mountain Aquifer of the West Bank and Israel

The spatial trajectory of water of what is generally called the Mountain Aquifer can be first conceived over a wider scale as three types of flows: the western aquifer flows westward toward Israel; the eastern aquifer flows eastward toward the Jordan Valley; and the northeastern aquifer flows northward towards Israel. These flows are illustrated in Figure 10-1.

Actually, the karstic soil of the West Bank means that the unconfined upper aquifer is commonly underlain by other aquifers separated from each other by a mostly impermeable layer of soil. These aquifers are linked in places through cracks in the rocky soil for instance, but are notoriously difficult to model and represent in a three-dimensional fashion. Nevertheless, within each basin, the groundwater flow of these aquifers aims in the same direction: westward or northward toward Israel or eastward toward the Jordan Valley. Applying our water trajectory approach means that we follow this flow in that direction within each basin.

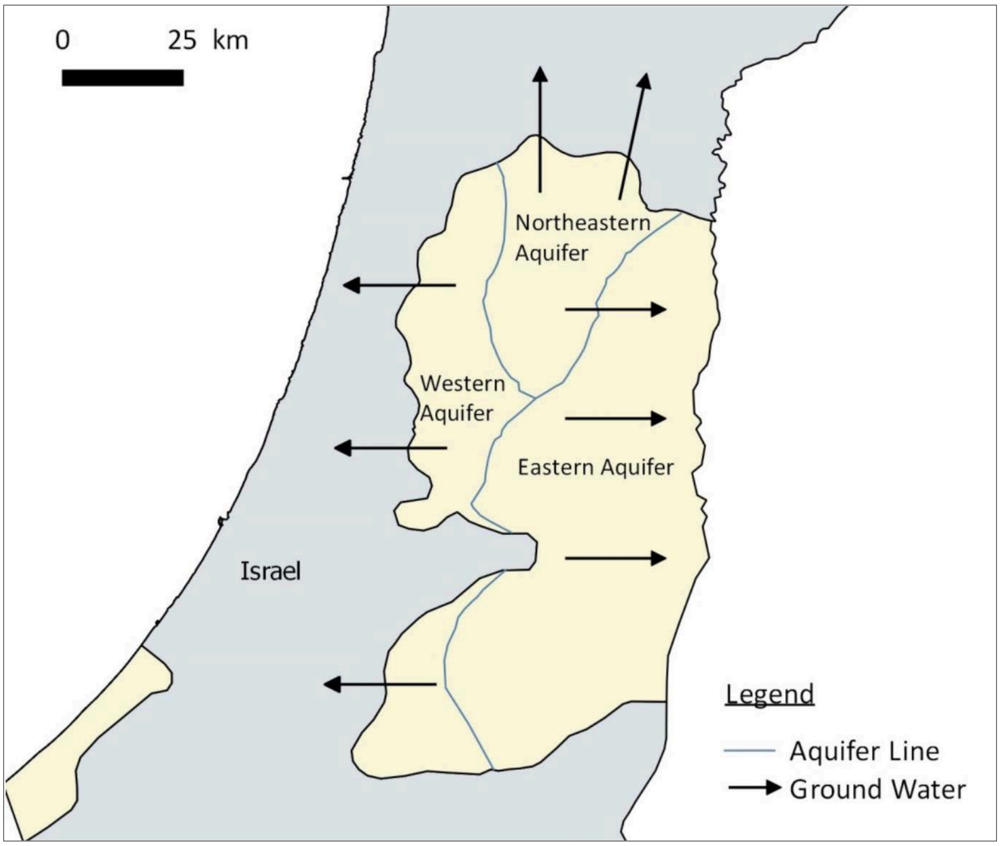


Figure 10-1 *Rough Spatial Water Trajectories over the Scale of the West Bank (Source: authors using QGIS)*

06

Three Case Studies of Water Security Issues in the West Bank

6.1. Interactions between Wells and Springs in Al Far'a Valley

Several perennial springs, such as 'Ein Miska, 'Ein al-Far'a and 'Ein Shibli, showed strong flows until very recently all along the Al Far'a Valley that stretches eastward from the outskirts of Nablus toward the Jordan Valley. Guérin, a French explorer of the nineteenth century who mapped the area, indicates the existence of water mills along their banks (Guérin, 1874). Although Al Far'a spring appears to lie above the northern aquifer, its flow was channeled eastward by an irrigation canal and these springs were linked to the groundwater flow of the eastern aquifer toward the Jordan Valley. Reliable all year long, they were the object of a common property regime that was elaborated locally to apportion their flow to the various farmers using it for irrigation. When purchasing or inheriting land, farmers would acquire simultaneously the "water right" linked to that land. This right was defined in terms of the length of time during which, and the frequency at which, the flow of the spring would be directed to the farmer's field. Each spring was thus managed by a grassroots, farmer-run, informal organization. This form of management was sustainable and never involved any payment for water. The stone channel had to be maintained, and the necessary work was carried out by the irrigating farmers themselves. This arrangement allowed both subsistence and commercial agriculture.

'Ein Miska spring and 'Ein al-Far'a spring started disappearing respectively in 1995 and 2005, dried up by the unlicensed sinking of new wells in the surrounding area by Palestinian farmers or investors (Tomazi & Naslun, 2005). 'Ein al-Far'a spring had previously discharged 5.5 million m^3/year, entirely channeled eastward. A 2.5 km stone channel had directed the flow of 'Ein Miska spring to 35 hectares of farmland within a regular rotation determined by the communal property regime governing it (Trottier & Perrier, 2018).
Every year between 1970 and 1994, this spring had discharged 1,317,000 cubic meters of water through a continuous flow (Tomazi & Naslun, 2005). Both springs have now become completely dry, even in the winter rainy season. The farmers relying on these springs either had to cut down their trees or buy water from the wells that dried up the springs they used to rely upon. The springs' drying up extinguished the institutions that had managed them. The spatial flow of water through Al Far'a Valley was only slightly altered as water keeps flowing, underground, towards the Jordan Valley. As unlicensed wells were drilled and the surface of commercially farmed land increased over tenfold, a greater share of this flow was deviated toward evapotranspiration. However, the institutional flow of water through this valley was fundamentally transformed. Water had previously been managed in a sustainable manner by farmer-run organizations on the basis of common property regimes within which water was never sold. Now, unlicensed wells drilled by individuals impose new institutions to govern this flow.

Jeanne Perrier carried out a detailed analysis of these unlicensed wells within her doctoral thesis (Perrier, 2020). She showed that they sometimes obtain a permit a posteriori. She showed that some of them are drilled as an investment, in order to generate a rent through selling water to neighboring farmers. Trottier and Perrier (2018) argued that such well owners achieve resource capture in an unregulated environment because they resort to technology, wells and pumps, that didn't exist when the local water tenure was elaborated concerning the springs. Older wells, such as those existing in the northwest of the West Bank, have written statutes and are managed by common property regimes. The unlicensed wells in Al Far'a valley have no written statutes and function under an unregulated private property regime. Perrier (2020) detailed the unsustainable management that ensues. The water level in the wells drops inexorably year after year, leading the irrigating farmers using them to consider that there won't be any irrigation in the valley in 20 years. The boom in commercial farming the valley has experienced since 1995 is thus expected to be short-lived and followed by a waterless future.

The unlicensed wells in Al Far'a valley are drilled by Palestinian farmers or investors using private funds. Israeli settlers play a similar role elsewhere. For instance, Elon Moreh settlement appropriated a spring that used to flow into the village of Deir Al Hattab. As Elon Moreh developed this spring for its own uses, it dried up the spring in Deir Al Hattab. Such appropriation of springs also affects Palestinian water security (Braverman, 2019). The important point demonstrated here is that the approach using water trajectories reveals important problems of water security emerging from interactions among Palestinian actors as well as emerging from Israeli settler action. When using a deductive approach, it is common for research to pose as its initial hypothesis that Palestinian water security problems arise from Israeli actions. Though this hypothesis may be correct, it is not necessarily so. The water trajectories approach, which we outline below, allows an inductive approach that reveals hitherto unstudied actors.

Another important result from the use of the water trajectories approach consists of its revealing the institutions interacting successively along the same flow of water, even when they have yet to be recognized formally. Farmer-run common property regimes governing springs have yet to be recognized by the Palestinian water law. Unlicensed wells, by definition, are not recognized by national authorities. The evolution of the institutional trajectory of the water explains the present threat to water security in Al Far'a valley. Until now, this institutional trajectory has not shown the

Palestinian Water Authority among the institutions involved successively in managing the flow of water. We defined water security as a situation where the governance over all scalar levels ensures an interaction with the flow of water that is consensually considered equitable across all social groups while ensuring the sustainability of the environment. Clearly, in Al Far'a valley, farmers who used to rely on springs do not consider the interaction unlicensed wells have with the flow of water to be legitimate or equitable. These interactions are understood, even by the unlicensed well owners, as environmentally unsustainable. This raises the issue of how can water governance be improved, in such a case, in order to reach a state of water security. We will return to this point in the discussion section.

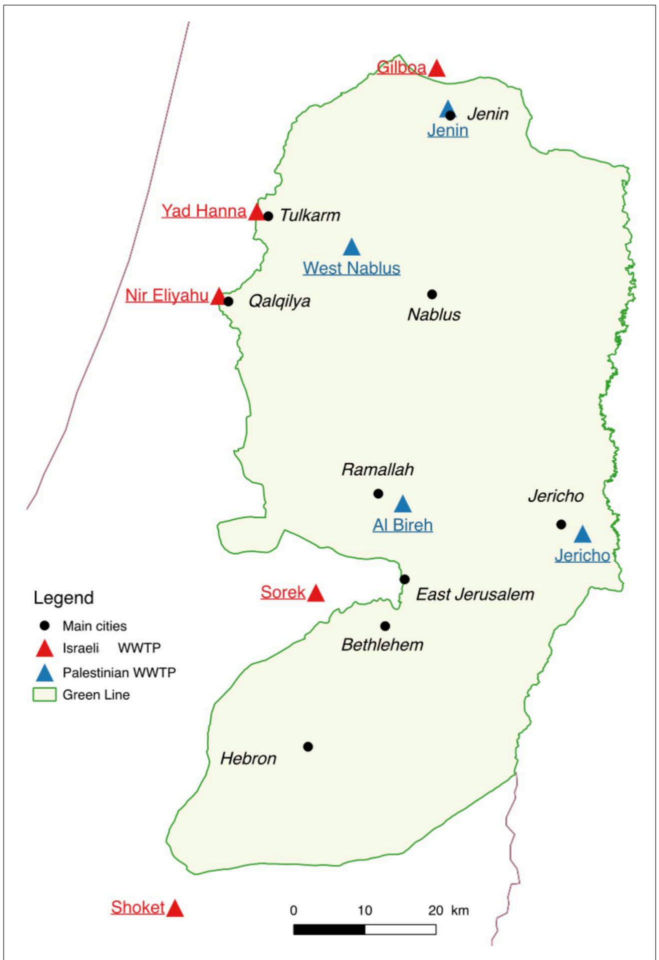


Figure 10-2 *Wastewater treatment plants in Israel treating wastewater from the West Bank (Source: authors using QGIS)*

6.2. Wastewater Reuse

The water trajectory approach is especially useful to examine the impact of treated wastewater reuse projects on water security. Most conferences and papers on the reuse of treated wastewater open with a reflection on the "creation of resources" that is offered by the reuse of treated wastewater. This was the case, for instance, for nearly all the papers presented at the Stockholm Water Week conference in 2017, when this yearly international venue focused on waste water. Most often, the release of treated wastewater into the environment is considered to be a "waste". Generally, this conclusion is inaccurate. A reuse project proposes to direct treated wastewater into a new spatial, institutional, and, in many cases, sectoral trajectory. This means it simultaneously proposes to divert the present flow of treated (or untreated) wastewater from its present trajectory. Treated wastewater released into the environment recharges shallow aquifers and thus contributes to supplying agricultural wells and springs located downstream. Examining the changes this involves allows determining whether water security was improved or worsened through a reuse project.

The Palestinian Authority (PA) is especially concerned by the surface wastewater that flows through the Green Line into Israel. Israel has used the import duties it levies on goods imported into Palestinian territory to build and operate five wastewater treatment plants (WWTPs), inside Israel, that treat the flow of wastewater incoming from the West Bank at six entry points (Fischhendler *et al.*, 2011) as shown on Figure 10-2.

Israel charges the PA yearly for the cost of treating this wastewater on the basis of the volume that crosses the Green Line. This means the bill includes the portion of this flow that was already treated by a Palestinian WWTP.
This is the case, for instance, with the wastewater flowing into Israel close to Tulkarem; part of this flow originates from the outlet of West Nablus treatment plant. This also means the bill covers the portion of this flow that originates from an Israeli settlement located in the West Bank. Typical annual bills are substantial. In 2017, Israel billed the PA US$31 million for treating 21,400,000 m^3 of wastewater that flowed through the Green Line. Having paid for the infrastructure cost and the operation cost for this treatment, the PWA considers the treated wastewater should be given to Palestinians. Instead, it is directed to Israeli farmers.

As early as 2013, the National Water and Wastewater Strategy for Palestine aimed to direct, over the long term, most treated wastewater to irrigation, leaving only 40% to replenish the aquifers (Palestinian Water Authority, 2013). The Strategy argued this would allow reducing the pressure of irrigation on the aquifers and projected a concomitant decrease in groundwater abstraction of 21 Mm^3/year over the long term. Wastewater reuse project documents also usually state in their introduction that their goal is to reduce the pressure on the aquifer. Yet, none of the wastewater reuse projects so far have supplied previously irrigating farmers with treated wastewater. Such projects have systematically channeled water to land that was previously rain-fed or uncultivated. The choice of crops to be irrigated, made by the projects, such as fodder in the case of West Nablus and Jenin, is coherent with maximizing evapotranspiration in order to decrease as quickly as possible the flow of wastewater crossing through the Green Line, thereby reducing the hefty bill Israel sends the PA.

The water trajectory approach is especially useful to examine the manner wastewater reuse projects affect water security. The spatial, institutional, and sectoral trajectories followed by treated wastewater once it is released by the WWTP needs to be assessed before and after the planned reuse project. Water flows put forward as being “wasted” may prove to be feeding springs and wells used for agriculture. Conversely, water flows which the reuse project plans to bring to previously rain-fed land often entails unwelcome changes in land tenure. Reuse projects are systematically planned by the Palestinian Authority, often with the support of international donors. They are thus elaborated in accordance with the Palestinian Law on Agriculture No. 2 of 2003. In effect, this law prohibits using treated wastewater when irrigating anything but fodder or fruit trees. As a result, reuse projects rule out the irrigation of other crops. This often means a change in the crops that is incompatible with the existing form of land tenure.

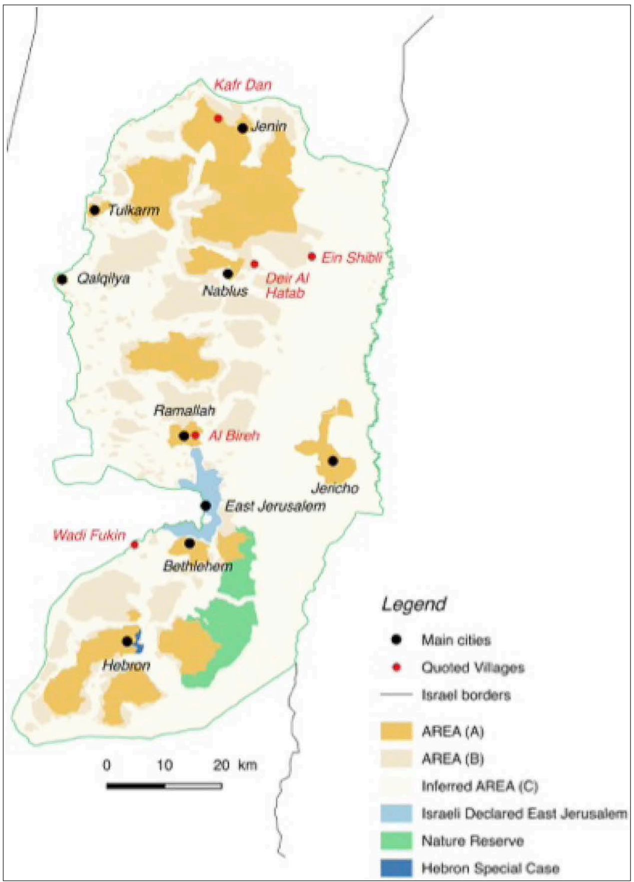


Figure 10-3 *Towns and villages mentioned in this chapter (Source: authors using QGIS)*

Land tenure in the West Bank is characterized by very small plots of land. In the western basin, most farmers either rent or own the plots they cultivate. In the eastern basin, sharecropping is far more widespread with only a minority of farms directly cultivated by the land owner. The differences in land tenure help explain the different impacts reuse projects have on water security. The only successful reuse project so far took place north of Jenin. The outflow of Jenin’s WWTP was channeled to formerly rain-fed fields north of the plant. The farmers who chose to take part in the project raise sheep. Irrigating fodder was a worthwhile activity for them as it made their individual contribution to the project profitable. The ongoing irrigation using treated wastewater from Jenin’s WWTP has had an unforeseen result: licensed agricultural wells – managed under a common property regime - in the neighboring village of Kafr Dan started supplying water once again, after having been dry for over a decade. As these are agricultural wells, the quality of their water is not closely monitored, so the impact of this recharge on water quality is unknown. This is an example of an “unwitting water use” resulting from this reuse project. The irrigation network from the WWTP is mostly buried 20 cm underground in order to protect farmers from health hazards. Clearly, water has percolated through the soil and replenished the aquifer. Such “wastage” has restored a spatial and institutional water trajectory that had disappeared together with much of the flow into the aquifer. Most of the licensed agricultural wells in neighboring villages have become dry since 2006.
An increasing flow of wastewater is expected to be directed to Jenin’s WWTP in the coming years as the sewerage network continues connecting more homes. This increased flow could be devoted to recharging wells and springs that have become dry.

Elsewhere, reuse projects have met much opposition.
The most land expansive reuse project among those linked to West Nablus WWTP expects a deep transformation of crops and land tenure. Here, most land owners maintain rain-fed olive trees on very small plots. They rely on urban activities for income and use their olive grove only for home consumption. Olive trees are ideal for part-time farmers. They require significant labor at planting and watering of young trees, and at harvesting, but only a little in between.
The reuse project plans to change the land cover to either fruit trees of four kinds, none of them including olives or fodder. The project expects land owners to aggregate their small plots into bigger exploitations that they will rent to a full-time farmer in order to grow irrigated fodder using treated wastewater that will be billed to the farmer. This project was not discussed with present land users, whether owners or renters, and meets much resistance. However, the greatest upheaval in water security through wastewater reuse in the next few years will probably occur in the Jordan Valley which we discuss in the next subsection.

6.3. Irrigation in the Jordan Valley

Understanding the impact of wastewater reuse on water security requires an understanding of water trajectories originating from other sources than WWTPs, and of the manner interactions with water flows are linked to food security, housing security, and income security. Whether or not water governance is considered equitable depends on whether it affects various forms of security positively or negatively.

The 2013 PWA strategy aims to direct most of the reused water to the Jordan Valley to irrigate date palm trees (Palestinian Water Authority, 2013). Israeli settlers started growing medjool date palm trees in the Jordan Valley in the 1970s. This cultivar requires an extremely dry and hot climate such as prevails there. The international demand for medjool dates is such that its selling price remains relatively inelastic with regard to supply. Consequently, medjool date palm trees have been sweeping through the valley at an accelerating rate. Israeli settlers' date palm trees went from covering 524 hectares in the valley in 1999 to 2560 hectares in 2016. Palestinian grown date palm trees went from covering 25 to 1584 hectares in the same time period (Trottier *et al.*, 2020). The cultivation of dates in the Valley is usually promoted on the basis of its water efficiency (Abu-Qaoud, 2015; Sonneveld *et al.*, 2018) and profitability (Zawahrah, 2016; Russo *et al.*, 2018). Using the water trajectory approach, however, sheds a more critical light on this agricultural development.

Israeli settlers' date palm trees in the Jordan Valley are entirely grown using wastewater channeled from Jerusalem, Maale Adumim, and Bethlehem area. A series of WWTPs along the Jordan Valley collects this wastewater and distributes it to the land cultivated by the settlements. The flow along this trajectory is entirely managed by Israeli authorities up to the WWTP. From that point, the settlers manage the flow to their trees. However, Palestinian date palm trees with the exception of the plots irrigated with treated wastewater from the Jericho WWTP, are entirely irrigated from groundwater wells located in the valley. Palestinian agribusinesses identify water supply as the main uncertainty in their business plans in order to keep expanding their plantations. They champion the construction of a trunk line that would bring the treated wastewater generated by Al Bireh's WWTP, located south of Ramallah, to the valley. Currently, this treated wastewater is released into the environment. Such a trunk line would create a new spatial trajectory as well as a new institutional trajectory for this flow.

The advent of date palm trees has transformed Palestinian land tenure significantly in the Jordan Valley. Sharecropping of small plots predominated until recently (Trottier, 2015). Agribusinesses are capable of renting large strips of land, sometimes 60 hectares at a time. When they do so, they fence their land and resort to seasonal laborers. Palestinian agribusinesses thus create jobs and generate foreign currency as the dates are exported. However, they displace sharecroppers when the land they rent had previously been cultivated. This entails deep social and economic changes that affect men and women differently. As opposed to a seasonal worker, sharecroppers lived on the land at least 10 months/year. They derived income security, housing security, and food security from their status as sharecroppers.
By 2016, date palm trees had, in effect, displaced over 7,000 sharecropper family members from the Jordan Valley (Trottier *et al.*, 2020). This number is a significant proportion of the 51,410 inhabitants of the Jericho and Al Aghwar governorate where the area suitable for medjool date cultivation lies.
The example of the Jordan Valley illustrates the necessity to examine both land and water tenure when assessing water security.

> *“Understanding the impact of wastewater reuse on water security requires an understanding of water trajectories originating from other sources than WWTPs”*

If the trunk line is built, linking Al Bireh and the Jordan Valley, the new spatial flow of water would be entirely managed by the Palestinian Authority. At present, this flow of water recharges the aquifer that feeds a variety of wells and springs used by farmer associations on the basis of common property regimes, or, in the case of unlicensed wells and some licensed wells, as a private property regime. Such a project aiming to eliminate "wastage" would dispossess these water users and eliminate their institutions. It would not, however, displace more sharecroppers from the valley, providing the treated wastewater is brought to currently uncultivated land. Such considerations have to be weighed in order to conclude whether such a project would enhance water security or worsen it.

07

Policy Implications and Recommendations for Next Steps

The water trajectories approach allows identifying processes of water governance that are either considered inequitable by groups of actors or are producing environmental harm. This allows understanding how water governance can be improved in order to reach a state of water security.

In the case of Al Far'a valley, suppressing the unlicensed wells would be perceived as inequitable because the Israeli authorities pour cement in such wells from time to time. If the Palestinian Water Authority was to adopt the same attitude, it would be perceived as an occupier. The Palestinian water law forbids drilling unlicensed wells. The fact so many wells have been drilled and keep being drilled shows that creating a law is not a solution. However, the treated wastewater that will flow from the future East Nablus treatment plant could be used as an incentive to reach a sustainable form of governance. This treated water could feed the aquifers supplying the springs and the wells, which would reassure well owners threatened by the current drop in the level of the aquifer. In exchange, the Palestinian Authority could request cooperation from well owners in agreeing to limit their abstraction rates. Of course, such a scenario would first require that the Palestinian Water Authority recognize the existence of the common property organizations managing the springs and the private well owners.

> *"The water trajectories approach offers an inductive method to explore water governance, revealing the many actors deploying strategies over whatever scalar level they choose"*

In the case of wastewater reuse projects, the water trajectories approach could be incorporated in the environmental and social impact assessments. The spatial, institutional, and sectoral trajectories of treated wastewater existing before the reuse project need to be assessed. The various users of these flows, including the environment, need to be identified and included in the consideration of the project because they would lose their access to water once the reuse project becomes operational. Otherwise water security may be damaged by reuse projects.

In the case of irrigation in the Jordan Valley, the transformation of land tenure and its impact on food security, income security, and housing security needs to be assessed. The construction of a trunk line to carry treated wastewater from Al Bireh to the Jordan Valley could improve water security only if its outlet lies on currently uncultivated land. However, if it reaches cultivated land, the fate of sharecroppers has to be considered. Moreover, the long-term consequences of drip irrigation in the Jordan Valley must be considered. Salt builds up at the foot of date palm trees. Water security requires an environmentally sustainable use of water. Washing off the salt in order to prevent soil sterilization must be part of water governance that ensures water security.

The water trajectories approach offers an inductive method to explore water governance, revealing the many actors deploying strategies over whatever scalar level they choose. It allows incorporating transboundary management issues, such as the bill Israel charges for wastewater crossing the Green Line, with local food security issues, such as Khubbezeh growing thanks to leaks and thus ensuring a healthy diet for the poor. It allows incorporating land tenure and water tenure issues. This is essential because any change in land use has implications on water.

08
Conclusion

Water flows are such an important part of the hydrogeography of land that any change in land use or infrastructure will have an effect on their spatial, institutional, or sectoral trajectory—and possibly two or all of them. What that effect will be, and the extent to which it will promote or reduce water security, as defined above, needs to be assessed scientifically and considered democratically before such changes are made.

> *"Water flows are such an important part of the hydrogeography of land that any change in land use or infrastructure will have an effect on their spatial, institutional, or sectoral trajectory"*

Past negotiations between Israeli and Palestinian authorities have focused on securing a stock of water (Brooks & Trottier, 2020). A paradigmatic reformulation of their stakes in terms of flow opens much broader possibilities for devising forms of water governance that will ensure water security to both parties. However, such a paradigmatic shift is also useful over a national, or even a smaller, scale. It can allow improving water governance inside a national territory or inside a valley.

The conceptualization of water security and the methodology to explore it that is presented here cuts across academic disciplines and paradigms. It allows interdisciplinary teams to collaborate even when their members subscribe to different paradigms. Using the concept of water security put forward in this paper, and the water trajectories approach to assess it, is especially useful in the case of transboundary surface and subsurface water flows. This inductive approach reveals many stakes and many actors that are invisible within a discourse built on the securitization of water. It also promotes a form of governance that can provide long term stability because it addresses their issues in a comprehensive manner.

References

AAbu-Qaoud, H. (2015). Date Palm Status and Perspective in Palestine. In Al-Khayri, J. M., Jain, S. M. & Johnson, D. V. (eds.) *Date Palm Genetic Resources and Utilization*. Springer, Dordrecht, pp. 423–438.

Aggestam, K. (2015). Desecuritisation of water and the technocratic turn in peacebuilding. *International Environmental Agreements: Politics, Law and Economics*, 15, pp. 327–340. https://doi.org/10.1007/s10784-015-9281-x.

Bakour, Y. & Kolars, J. (1994). The Arab Mashrek: Hydrology, History, Problems, Perspectives. In *Water in the Arab World : Pespectives and Prognoses*. Harvard University Press, Cambridge, MA, pp. 121–146.

Beaumont, P. (2002). Water policies for the Middle East in the 21st century: the new economic realities. International Journal of Water Resources Development 18.

Boelens, R. (2015). Water, Power and Identity. The cultural politics of water in the Andes. Routledge, London.

Braverman, I. (2019). Silent springs: The nature of water and Israel's military occupation. Environment and Planning E: Nature and Space 251484861985772. https://doi.org/10.1177/2514848619857722.

Brooks, D., Trottier, J. & Giordano, J. (2020). Transboundary Water Issues in Israel, Palestine and the Jordan River Basin: An Overview, Springer Nature. ed. Singapore.

Brooks, D. B. & Trottier, J. (2012). An Agreement to share water between Israelis and Palestinians: The FoEME proposal. Revised Version.Friends of the Earth–Middle East (FoEME).

______. (2014). De-nationalization and de-securitization of transboundary water resources: the Israeli-Palestinian case. Int. J. Water Resour. Dev. 30, pp. 211–223. https://doi.org/10.1080/07900627.2013.849941.

______. (2020). Moving water from last to first in the Middle East peace process. International Journal of Water Resources Development 1–5. https://doi.org/10.1080/07900627.2020.1787126.

Bruns, B. R. & Meinzen-Dick, R. S. (2001). Water Rights and legal pluralism: four contexts for negotiation. Natural Resources Forum 25, 1–10.

Cook, C. & Bakker, K. (2012). Water Security: Debating an emerging paradigm. *Global Environmental Change*, 22, pp. 94–102.

Falkenmark, M. (2001). The greatest water problem: the inability to link environmental security, water security and food security. *International Journal of Water Resources Development*, 17, pp. 539–554.

Falkenmark, M., Berntell, A., Jägerskog, A., Lundqvist, J., Matz, M. & Tropp, H. (2007). On the Verge of a New Water Scarcity: A Call for Good Governance and Human Ingenuity, SIWI Policy Brief. Stockholm International Water Institute, Stockholm.

Falkenmark, M. & Molden, D. (2008). Wake up to realities of river basin closure. *International Journal of Water Resources Development*, 24, pp. 201–215.

FAO (Forthcoming). Water Auditing: Water Governance Analysis A Methodological guide.

______. (2020). Unpacking water tenure for improved food security and sustainable development. FAO. https://doi.org/10.4060/cb1230en.

Feitelson, E., Tamimi, A. & Rosenthal, G. (2012). Climate change and security in the Israeli–Palestinian context. *Journal of Peace Research*, 49, pp. 241–257. https://doi.org/10.1177/0022343311427575.

Fischhendler, I. (2015). The securitization of water discourse: theoretical foundations, research gaps and objectives of the special issue. *International Environmental Agreements: Politics, Law and Economics*, 15, pp. 245–255.

Fischhendler, I., Dinar, S. & Katz, D. (2011). The Politics of Unilateral Environmentalism: Cooperation and Conflict over Water Management along the Israeli-Palestinian Border. *Global Environmental Politics*, 11, pp. 36–61.

Floress, K., Thompson, A. & LeBlanc Fisher, C. (2019). Assessing Principles of Good Governance: The Case of Lake Wausau, Wisconsin. Journal of Contemporary Water Research & Education pp. 97–109.

Forsyth, T. (2003). Critical Political Ecology: the politics of environmental science. Routledge, London.

Fustec, K. & Trottier, J. (2016). Quelle contribution des SHS dans la production des savoirs sur l'eau et le changement climatique? Le cas des projets de recherche financés par l'Union Européenne. *Sciences de la société*, pp. 103–118.

Galtung, J. (1969). Violence, Peace and Peace Research. *Journal of Peace Research*, 6, pp. 167–191.

Guérin, V. (1874). Description géographique, historique et archéologique de la Palestine accompagnée de cartes détaillées. Amsterdam Oriental Press 1969, Paris (1974) Amsterdam (1969).

Haviv, I. & Asaf, L. (2005). The Hydrological System of Wadi Fuqeen Springs. Friends of the Earth Middle East, Tel Aviv.

Hodgson, S. (2016). Exploring the Concept of Water Tenure, Land and Water Discussion Papers. Food and Agriculture Organization of the United Nations, Rome.

IWRA. (2020). Water Security and the Sustainable Development Goals (No. 4), Policy Brief. IWRA.

Kronich, Sh. & Maghen, L. (2020). Ensuring Water Security in the Middle East:

Policy Implications (Euromesco Policy Study No. 15). European Institute of the Mediterranean, Barcelona.

Mabry, J. B. (1996). Canals and communities : small-scale irrigation systems, Arizona studies in human ecology. University of Arizona Press, Tucson.

Malekian, A., Hayati, D. & Aarts, N. (2017). Conceptualizations of water security in the agricultural sector: Perceptions, practices, and paradigms. *Journal of Hydrology*, 544, pp. 224–232. https://doi.org/10.1016/j.jhydrol.2016.11.026.

Palestinian Water Authority. (2013). National Water and Wastewater Strategy for Palestine.

Perrier, J. (2020). Quelle gouvernance des eaux pour quelle construction étatique dans les territoires palestiniens? L'étude des constellations hydropolitiques des eaux douces et usées: entre adaptation, fragmentation et colonialité (doctorat). Université Paul Valéry, Montpellier, France.

Russo, G., Dalla Ragione, I., Fantinati, L., Simonetti, C. & Lauteri, M. (2018). A Socio-ecological Analysis of the Date Palm (Phoenix dactylifera L.) System in Jericho Area, Palestine. In Kallel, A., Ksibi, M., Ben Dhia, H. & Khélifi, N. (eds.) *Recent Advances in Environmental Science from the Euro-Mediterranean and Surrounding Regions*. Springer International Publishing, Cham, pp. 1425–1427. https://doi.org/10.1007/978-3-319-70548-4_416.

Sher, Gilead. (2018). Israel 70 / Ramifications of a Termination of the Oslo Accords. *Fathom*.

Sonneveld, B. G. J. S., Marei, A., Merbis, M. D., Alfarra, A. (2018). The future of date palm cultivation in the Lower Jordan Valley of the West Bank. *Applied Water Science*, 8, p. 113. https://doi.org/10.1007/s13201-018-0746-2.

Tomazi, A. H. & Naslun, S. (2005). Water Rights. In Abdulfattah, K. & de Vries, B. (eds.) *Wadi El-Far'a Project Report: An Environmental Assessment of the Wadi El-Far'a Watershed, The Lower Jordan River Basin Programme Publications*. Bir Zeit University, Ramallah, pp. 118–140.

Trawick, P. (2015). Le rapport à l'eau et à la terre dans la construction de territoires multisitués: le cas palestinien. *L'Espace Géographique*, 2, pp. 103–114.

Trottier, J. (1999). Hydropolitics in the West Bank and Gaza Strip. PASSIA, Jerusalem.

_____. (2002). Comedy and Tragedy in the Andean Commons. Journal of Political Ecology, 9, pp. 35–68.

_____. (2007). A wall, water and power: the Israeli "separation fence." Review of International Studies, pp. 105–127.

Trottier, J., Leblond, N. & Garb, Y. (2020). The political role of date palm trees in the Jordan Valley: The transformation of Palestinian land and water tenure in agriculture made invisible by epistemic violence. *Environment and Planning E: Nature and Space*, 3, pp. 114–140. https://doi.org/10.1177/2514848619876546.

Trottier, J. & Perrier, J. (2018). Water driven Palestinian agricultural frontiers: the global ramifications of transforming local irrigation. *Journal of Political Ecology*, 25, pp. 292–311.

Trottier, J., Rondier, A. & Perrier, J. (2019). Palestinians and Donors Playing with Fire: 25 years of Water Projects in the West Bank. International Journal of Water Resources Development. https://doi.org/10.1080/07900627.2019.1617679.

Vörösmarty, C. J., Rodríguez Osuna, V., Cak, A. D., Bhaduri, A., Bunn, S. E., Corsi, F., Gastelumendi, J., Green, P., Harrison, I., Lawford, R., Marcotullio, P. J., McClain, M., McDonald, R., McIntyre, P., Palmer, M., Robarts, R. D., Szöllösi-Nagy, A., Tessler, Z. & Uhlenbrook, S. (2018). Ecosystem-based water security and the Sustainable Development Goals (SDGs). *Ecohydrology & Hydrobiology*, 18, pp. 317–333. https://doi.org/10.1016/j.ecohyd.2018.07.004.

World Bank. (2018). Toward Water Security for Palestinians. World Bank.

Zawahrah, K. M. (2016). Using the Policy Analysis Matrix to Analyze the Effect of Economic Policies on Medjool Dates in Palestine (Master's Thesis). Bir Zeit University, Bir Zeit.

11

Transbounday Groundwater, Peace and Security: Opportunities and challenges in Central America

Maureen Walschot and Wagner Costa Ribeiro

Maureen Walschot, International Relations & Geography, Université catholique de Louvain, Belgium & University of Haifa, Israel.
e-mail: Maureen.walschot@uclouvain.be
Wagner Costa Ribeiro, Geography, Universidade de Sao Paulo, Conselho Nacional de Desenvolvimento Científico e Tecnológico, Brazil.
e-mail: wribeiro@usp.br

Abstract

As water can act as a threat multiplier as well as enhance cooperation, this paper looks at opportunities and challenges regarding peace, water security and transboundary aquifer management in Central America. Based on the concept of a hydro-security complex, the paper highlights and develops the water-peace nexus in the region.
Central America, a region characterized by conflicts, has several transboundary water bodies, be it groundwater or surface water. The joint management of transboundary aquifers, as well as other transboundary resources, lies often in a difficult balance of different interests and uses among the relevant riparian actors.
This paper offers a better understanding of the nexus between peace, water security and transboundary aquifers in a region often understudied. A thorough analysis of the different legislative, institutional and negotiation characteristics of the region over transboundary aquifers management is another important outcome of the research. Finally, the paper builds on a new facet of water security, with the inclusion of the regional context and a deeper understanding of the hydro-political complex theory.

Keywords

Groundwater, water security, peace, Central America

01
Background

Water can act as a threat multiplier as well as enhance cooperation, partly forging opportunities and challenges regarding peace, water security and transboundary water management. Hydro-politics have long mainly focused on surface water basins. However, this approach to surface watersheds has precluded a real analysis of groundwater resources, which are as much exposed to over-exploitation and pollution phenomena as surface waters, if not more. Nevertheless, the consequences of such phenomena are not visible in the short term, which has often led to inadequate or close to no action. However, the increasing depletion and contamination of these groundwater resources are putting at risk water security at the international, national and local levels.

> *"The increasing depletion and contamination of groundwater resources are putting at risk water security at the international, national and local levels"*

Central America is a region characterized by insecurity and violence. It also has several transboundary surface and groundwater basins. The presence of these internationally shared watersheds forces the riparian States to adapt their water management. Such a constraint can strengthen cooperation or, on the contrary, exacerbate or create conflicts. The joint management of transboundary aquifers, as well as other transboundary resources, lies often in a difficult balance of different interests and uses among the relevant riparian actors.

This paper develops a new facet of water security, with the inclusion of the regional context and a deeper understanding of the hydro-political complex theory. First, this paper identifies the existing enabling factors of cooperation in each transboundary aquifer system of the region. Second, rejecting the conflict/cooperation dichotomy, this paper then analyzes transboundary water interactions among parties, using the TWINS model to determine their level of interaction. By combining the two, it establishes the level of engagement among states regarding transboundary aquifers in the region. Finally, the paper also presents recommendations on how to improve existing tools and create new ones.

Challenges to water security exist, such as access, availability or conflict over water issues (Grey *et al*.,. 2007). These are reinforced by increasing consumption by mankind and increasing population, contamination and degradation of water resources, as well as climate change (Beisheim, 2013; Gleick, 1993). According to Conti in the International Groundwater Resources Assessment Centre (IGRAC) report, "it has been determined that there is enough water available to meet human needs, but poor resource management consistently undermines attempts to properly allocate and conserve the global water supply" (Conti, 2014, p. 9). According to Albrecht *et al*. (2017), water security becomes even more complex when the resource crosses or forms part of an international border. The authors have established recommendations for governance mechanisms to enhance transboundary groundwater security that are developed later in this paper.

In this context, it is therefore crucial to identify transboundary water management challenges and opportunities in order to articulate sound practices of transboundary water governance (INBO & GWP, 2012). Balancing water use among the different relevant sectors and stakeholders is part of the equation, as well as moderating the different aforementioned threats is critical to moderate water interactions, be they local, national or international (Abukhater, 2013). Despite the ongoing debate on water as a factor of conflict or cooperation, several studies have shown that interactions over transboundary water are mostly cooperative (Wolf, 2007). However, according to Conti, "the discourse about cooperation and conflict is often disjointed to the point that it presents two false dichotomies. The first is that cooperation and conflict are mutually exclusive and occur in opposition to each other. The second that cooperation is 'good' and that conflict is 'bad'" (Conti, 2014, pp. 8-9).
As a matter of fact, water interactions between two riparian actors are often simultaneously characterized by different levels of cooperation and conflict (Ribeiro *et al*., 2014; Perlman *et al*., 2017). This paper is therefore based on the analysis of interactions among governing states responsible for transboundary aquifers, using the TWINS model to indicate their level of interaction and engagement over a transboundary aquifer and coupling this level with enabling factors. Through inductive research derived from official documents and secondary sources analysis, this paper intends to answer the following research question: What is the state of water cooperation in Central America?

1.1. Transboundary Groundwater, Peace and Security in Central America

Figure 11-1 *Map of Central American Countries (Source: PeterHermesFurian, retrieved from GWP, 2016, p. 8)*

Central America is composed of seven countries: Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama (see Figure 11-1). The region is a complex mix of different climatic and natural environments, as well as different cultures and populations (CEPAL, 2015). Looking at the "history of the region over the past few centuries provides insights into how nations have developed and are inescapably connected by their borders, by water resources, and by the environment" (GWP, 2016, p. 6). In the 1990s, rural development policies, as well as environmental conservation measures, were put into place to enhance transregional cooperation. Nowadays, "numerous international cooperation initiatives now seek to preserve biodiversity, water, and other basin assets through projects that have introduced the international community's concerns and interests into local management" (GWP, 2016, p. 6).

Central America is endowed with water resources (see Table 11-1). With the regional average daily per capita water available estimated at over 68,000 liters (FAO AQUASTAT2, n.d.), levels of fresh water availability are above scarcity and water stress levels. According to the environmental sustainability dashboard of the 2019 Human Development Index, the available abstraction rate by country across the Central American region is low (UNDP, 2014). Panama, Costa Rica and Nicaragua are among the top third countries whose freshwater withdrawals are a low percentage of the total renewable water resources[1]. However, according to the GWP, water scarcity remains a concern in the region given "the lack of mechanisms and actions for managing, allocating, and developing water resources" (GWP, 2016, p. 10).

Vulnerability to climate change is a critical issue in Central America (CEPAL, 2015). Amongst various extreme events, droughts are particularly influencing the state of water security and challenging water governance and access for the populations (GWP, 2016). These last few years, what is called

Table 11-1 *Central America: annual water resources (Source: GWP, 2016:10)*

Country	Total internal renewable water resources (km^3)	Total internal renewable water resources (km^3)	Total (km^3)	Dependence[2] (%)	Water resources per capita (m^3)	Annual fresh water extraction (km^3/year)
Belize	15.25	6.474	21.73	29.8	65,452	0.8
Costa Rica	113.00	0	113.00	0	23,194	2.4
El Salvador	15.63	10.640	26.27	40.5	4,144	3.8
Guatemala	109.20	18.710	127.90	14.6	8,269	2.6
Honduras	90.66	1.504	92.16	1.6	11,381	1.2
Nicaragua	156.20	8.310	164.50	5.1	27,056	0.7
Panama	136.60	2.704	139.30	1.9	36,051	0.3

the 'dry corridor', a portion of territory along the west coast of El Salvador, Guatemala and Honduras, has experienced extreme droughts. In 2016, over 3.5 million people, mostly rural populations, needed humanitarian assistance as a consequence of these climate events. The 'dry arch' along the west coast of Panama has experienced a similar situation (GWP, 2016, p. 11). Besides these climate events affecting water security, it is noteworthy to acknowledge that all States are interconnected through 23 international watercourses and 18 transboundary aquifers. Therefore, according to the Global Water Partnership, "a key feature of water resources planning and management is about finding agreeable ways of sharing water resources, which both cross and form national boundaries, and applying the principles of integrated water resources management (IWRM)" (GWP, 2016, p. 11).

Despite the existence of several joint management projects, cooperation over transboundary groundwater, or any transboundary body of water, is still nascent in the region (Sindico, 2019). The national legal systems for water governance are however developing, sound and explicit national regulations being a preliminary condition to transboundary cooperation (Burchi, 2018). According to GWP, "recent relations between Honduras and Nicaragua are discussed, Guatemala and El Salvador are, however, lagging behind and still lack legal and institutional water frameworks" (GWP, 2016, p. 11).

"Despite the existence of several joint management projects, cooperation over transboundary groundwater, or any transboundary body of water, is still nascent"

Given the number of internationally shared water resources, cooperation and joint management is critical to minimize tensions and unsustainable use. Nevertheless, "even when there is willingness to cooperate in exploiting and protecting transboundary water basins (in Costa Rica, El Salvador, Guatemala, Honduras, and Panama), the intergovernmental instruments signed so far have proved insufficient to establish and implement agreements for managing and integrating development of international watercourses. Such instruments do not even exist between Costa Rica and Nicaragua" (GWP, 2016, p. 11). Given this lack of institutional capacity and joint instruments, it is harder to accommodate conflicts of interest among the different stakeholders (Jiménez *et al*., 2020). As long as these will be missing, the transboundary aspect of the integrated water resources management approach will be hard to fulfill in the region.

Be it at the national or international level, studies have shown how governance risks are at the highest level regarding aquifers in Central America. Governance risks are also the highest level of risk when looking at all categories of water systems (ILEC *et al*., 2016, p. 3). Therefore, assessing the right tools to ensure a sound governance of transboundary groundwater is needed. At the international level, research shows that in order for States to cooperate and successfully manage transboundary waters, communities of interests have to be recognized (Eckstein *et al*., 2005; Ribeiro, 2008; Villar *et al*., 2011; Ribeiro *et al*., 2014; Villar *et al*., 2018; Hatch Kuri, 2018). It means that each riparian actor has to be provided with specific and measurable benefits that "are proportional to their obligations, duties, and responsibilities" (GWP, 2016, p. 6). Moreover, studies also highlight the need for the implementation of institutions to enhance discussion and to create room for dealing with specific issues at the highest governmental levels. According to the GWP, "It is recommended that States in the region adopt cooperation as a means for promoting integrated management of transboundary aquifers and watercourses as a path to national and regional development. This means adopting the river basin management approach and taking into account the conventions, UN resolutions, and the vast global experience" (GWP, 2016, p. 6).

1.2. Enabling Transboundary Groundwater Cooperation

In her report for IGRAC, Conti developed eight enabling factors in transboundary aquifer cooperation (Conti, 2014, pp. 22-25). In this paper, we apply these enabling factors to all transboundary aquifers in Central America, in order to see what are the strengths and the flaws of the sub-region.

The first enabling factor is the existence of legal mechanisms, prior to cooperation. These mechanisms can vary. However, to be considered as an enabling factor in transboundary aquifer cooperation, they have to contain binding obligations on states.

The second enabling factor is the existence of regional institutions. Some of these institutions can act as an Enabling Factor for water cooperation, despite the fact that they don't encompass environment or water resources. However, they have to focus on groundwater in general or on a specific transboundary aquifer to function as an enabling factor.

The third enabling factor is the existence of funding mechanisms. In order to function as an enabling factor, funding mechanisms have to meet one of the two following criteria: 1) the aquifer states have to provide the funding, be it for the creation of an institution or for scientific or capacity building projects; 2) the funding is provided by a third party for projects or the creation of an institution.

The fourth enabling factor is the presence of high institutional capacity, meaning when organizations within the aquifer states are capable of addressing groundwater management issues. These organizations, including governments, have to be able to run projects to monitor, model or manage groundwater.

The fifth enabling factor is the existence of previous water cooperation. Such cooperation does not have to have happened among all aquifer states, or specifically on groundwater, to function as an enabling factor. In many cases, a strong institutional setting is often favoring cooperation over transboundary waters to continue over time.

The sixth enabling factor is the presence of scientific research, on the following conditions: 1) the scientific research has to deal with the assessment of aquifer management; 2) new data have to be provided by the aquifer states in a significant amount; 3) the scientific research has to take place prior to political cooperation on the aquifer, be it formal or informal.

The seventh enabling factor is the existence of a strong political will, resulting from high-ranking official action to put groundwater management high on the political agenda. Advocacy, openly expressed support or the organization or facilitation of diplomatic events are considered to be enabling factors.

The eighth enabling factor is third-party involvement, on the condition that third parties formally take part in the cooperation process related to groundwater management. It can be through formal partnerships or programs, such as contributing to the building up of scientific knowledge or working actively to promote institutionalized cooperation.

02

Transboundary Aquifers, Water Security, and Peace

2.1. Transboundary Aquifers

Aquifers are geological units capable of retaining water below the earth's surface. They are formed by porous rocks and soils resulting from natural processes that have occurred for centuries. The distribution of aquifers around the world derives from aspects inherited from nature. These units overlap the world's political divisions, which were defined through political and historical processes involving wars, agreements and domination of peoples.

By superimposing inherited sets of natural processes on national territorial units, it is often observed that many aquifers transcend the territorial limits of a country, thus extending over two or more countries. This condition results in a transboundary aquifer, which means that it is no longer only a natural aquifer, but a political unit, the management of which is much more complex.

Controlling water withdrawal and preventing contamination are major challenges involving the management of a transboundary aquifer. These challenges require the establishment of bilateral or multilateral agreements that define, a priori, the use of such water, as well as, and above all, the use of the soil on the surface that covers it, which is directly related to possible contamination of groundwater. Recharge areas must be given special attention because, in addition to replenishing water stocks, they can become sources of contamination if contaminated water or substances capable of reaching the water deposits begin to penetrate.

Establishing agreements between countries that hold an aquifer is fundamental to avoid tensions between them. However, in general, they arise after relations between parties have hardened (Eckstein *et al*., 2005). In the case of the Guarani aquifer, the situation was different, since the countries that hold the aquifer, Argentina, Brazil, Paraguay and Uruguay, were able to reach an agreement before a water conflict arose in 2010 (Villar *et al*., 2011, Leite *et al*., 2018).

Defining water security in an aquifer is even more difficult than in surface waters. This requires knowledge of the hydrogeology and recharging dynamics of the system that feeds groundwater, knowledge that is costly and time-consuming to acquire. This is why it is necessary to be cautious when using groundwater so as not to deplete sources at an early stage or generate tensions between countries.

2.2. Water Security

Water security can be perceived in different forms (Bakker, 2012; Jepson *et al*., 2017; Sadoff *et al*., 2020). In general, it is associated with two fundamental aspects: water supply; and, water quality. The combination of these variables can be verified in different geographical units. Thus, water security can be global (Ribeiro, 2008; Zeitoun, 2011; Ale *et al*., 2020), as well as national, regional, at a river basin level (Pahl-Wostl *et al*., 2012) and local (Sivapalan *et al*., 2012).

Water security should also ensure the maintenance of environmental and ecosystem services (Bakker, 2012). Therefore, quantifying the necessary volume of water for life in the various forms of social organization is one of the major difficulties faced by water security since this volume should not prevent the reproduction of environmental and ecosystem services.

The most relevant factor to consider in an analysis of water security is the available volume of water, which is obtained by the difference between rainfall and water retention capacity in a given locality and/or territorial unit. The retention depends on physical factors, such as evaporation (which is related to the geographical position, greater or lesser exposure to sunlight and land use – urban or rural, for example). In addition, the rocky substrate, in the case of an aquifer, and the type of soil cover, which can be more or less permeable, allows for greater or lesser infiltration. Furthermore, it is necessary to take into account the volume of water used within the territorial unit, which is directly associated with the way of life of the social groups living in it and, to a lesser extent, by the animals that live in the geographical unit.

> *“Quantifying the necessary volume of water for life in the various forms of social organization is one of the major difficulties faced by water security”*

Therefore, water security should not be viewed in terms of natural water reserves, regardless of whether they are surface, frozen or underground water, but rather in terms of the social and natural demands for water and the capacity to meet them. These characteristics are inserted in a geographical unit, that is why the political distribution of water imposes itself on its natural distribution (Ribeiro, 2008).

2.2.1. Water Supply

Undoubtedly, one of today’s greatest challenges is to guarantee water to the population. Several factors have led to situations of water stress or scarcity, which means that a significant part of the world’s population does not have access to water and, therefore, is nowhere near the established Human Right to water and sanitation, defined by the UN General Assembly in 2010. This makes the Sustainable Development Goals more difficult to achieve, in particular Goal 6, which aims to provide drinking water and sanitation to all by 2030.

Water stress is measured in several ways. It can be defined from the used volume of available water, but it can also be measured, for example, from the used volume of water reserves of a location or geographical unit. Scarcity is the lack of water, in quantity and quality, for basic reproductive actions of life. It occurs when available water is below demand.

In this scenario, there are localized crises of water supply distributed around the world. These crises are mainly the result of increased demand for water, especially for industrial and agricultural production, while failing to fulfill the replenishment capacity of water reserves. As a result, several sources of water in various locations are suffering shortages.

The hegemonic commodity production model uses water in industry and agriculture. In the first case, water contamination is verified after undergoing steps in the production process. The intentional addition of substances to water makes its treatment more expensive and contaminates surface and underground water bodies. In agricultural production, the intensive use of agrochemicals and other inputs cause high concentrations of pollutants to be found in the soil, which then migrate to rivers and aquifers, thus causing contamination.

Population growth is also a vector responsible for increased consumption. Urbanization related to population increase leads to greater demand for water. More water per capita is used in the urban environment than in the rural environment, which further increases the need to maintain water stocks over time. The growth of large cities, especially in middle- and low-income countries, and the emergence of megacities indicates that the water demand is not yet considered because, in many situations, the available water is not enough to maintain the water security of the town (Srinivasan, 2013; Jensen *et al*., 2018). Projections indicate that the largest cities of the 21st century will be in lower-income countries, which have greater difficulties in ensuring water supply.

Finally, it is important to remember that climate change can directly affect the water supply. Among the effects it brings are changes in rainfall regimes, as well as the intensification of extreme events, such as heavy rains and intense droughts (Hoegh-Guldberg *et al*., 2018). This set of factors alters water supply and water security in surface and groundwater.

2.2.2. Water Quality

Chemical elements are added to the water and change its natural characteristics. Due to its general solvent properties, water reacts to elements and chemical substances and becomes unsuitable for human and animal ingestion and, as well, it cannot be used for irrigation of agricultural areas or in parts of industrial processes.

There are several indicators of water quality, the most frequent being those that measure the amount of oxygen and its potability (Alam *et al*., 2007). Indicators quantify fecal coliforms or the presence of certain bacteria to measure and qualify the water that is found in a given location (van Leeuwen *et al*., 2012; Koop *et al*., 2015; Hoekstra *et al*., 2018).

One of the advances in recent decades has been the measurement of water quality either at the surface (in streams, rivers and natural lakes) or underground (in aquifers and/or groundwater) in several countries that previously did not measure it. The parameters regulating water quality in water bodies and aquifers are available in national institutions, but are still enough.

In rivers, the circulation of vessels, the presence of industries on their banks, the proximity of garbage dumps without adequate technical care, the in natura dumping of sewage, the storm water runoff from urbanized lands and the proximity of intensive monoculture cultivation with the use of pesticides are the greatest sources of contamination. These factors also affect aquifers. That is why it is necessary to control and avoid the release of substances to rivers. Aquifer recharge areas should be the main focus of monitoring, as they are the main sources of replacement of groundwater storage.

Water quality is directly associated with public health. Unfortunately, the lack of supply of quality water, as well as the absence of sewage collection and treatment, turns water into a vector of disease. This condition is scattered around the world and mainly affects populations in poorer countries.

With the increase in demand for water in industrial and agricultural production processes, for energy generation, to supply the population of large cities and megacities, demand for underground water sources has increased. The uncontrolled use of groundwater is one of the current concerns, as recharge can be much slower than the volume withdrawn. Intensive use also compromises water quality where water is returned to the environment without proper treatment, often resulting in contaminated water and therefore unfit for human and animal consumption.

2.2.3. Political Distribution of Water

Data such as rainfall and sun exposure in a given geographical unit are not the most important to define water security. It is necessary to consider the location of the water reserves, or the reservoirs built to store it. In other words, access to water has a territorial and political dimension and cannot be measured only in natural terms (Ribeiro, 2008).

The political distribution of water can be assessed based on the consumption by a given population in a geographical unit. This unit can be a municipality, a metropolitan area, a group of municipalities or even a river basin. The human demands within this area must be dimensioned, considering the multiple uses of water and the capacity of rainfall replenishment, minus evaporation and the water exported to other geographic units through trade in commodities or even industrialized products. As a result, the water supply can be adjusted in order to project future demands.

This type of analysis is rarely used. Conversely, numerous productive activities (agricultural and industrial) or dense urban concentrations are often installed in areas with low water replenishment capacity. As a result, there are areas with water stress or scarcity, which directly affects water security. The political distribution of water depends on social, geographic, historical, economic, political and cultural factors, which must be weighed against the available water.

The political distribution of water must be understood as the result between the volume of water needed and the supply of quality water in the water stocks of a territorial unit. It can be surplus or negative. Therefore, it is based on the social and economic demand for water, which must be associated with the demands for the maintenance of environmental and ecosystem services of a geographical unit, as well as its eventual capacity to supply water to other units.

2.3. Link between Water Security & Peace: Regional (or sub-regional) Hydro-security Complex

In this section, we analyze how water security and peace are linked in what we call a sub-regional hydro-security complex. First, in this paper, peace is defined not only by the absence of conflict but also by the absence of the possibility of potential conflicts, through risk-reduction strategies for example. Second, to elaborate on the notion of regional or sub-regional security complex, Moreno-Sainz develops in her work how "new threats" (meaning new to the policymakers and leaders) have emerged since 2001, and how environmental issues are one of them (Moreno-Sainz, 2017, p. 5). The author highlights that among the various features of these new threats is their transnational aspect, challenging sovereignty and action for States. These new threats are linked to internal and external issues, affecting defense and national security. Moreover, they are multidimensional (linked to economic, legal, social issues). More importantly, "they are able to create (or wake up) inter-states conflicts or disputes" and "they have the potential to produce problematic regions insofar as there are already several "no-go zones" (Pion-Berlin & Trinkunes, 2011): that means that there is a lack of effective sovereignty of the state over parts of some territories" (Moreno-Sainz, 2017, p. 5). According to Moreno-Sainz, States are challenged by these no-go zones where violent non-state actors are replacing the States by providing public goods. This is partially due to the lack of a strong justice system, and is preventing peace and security from happening (Moreno-Sainz, 2017, pp. 6-7; Pion-Berlin & Trinkunes, 2011, pp. 43).

Corruption involving water supplies is usual, unfortunately. In Central America this topic has been extensively studied, as well as in the water sector (Ruhl, 2011; Guasch *et al*., 2009). Indeed, management of water as a service can lessen present and future water scarcity or contamination that would lead to corruption and insecurity. The sound management of these transboundary sources is critical to strengthen the State action and intervention and to enhance security, peace and stability in the region (Plummer, 2008). Would the solution be in the creation of a sub-regional institution in Central America? There is already an impetus with the creation of the Agenda for sustainable water use in 2017[3], that aims at dealing with water issues as a matter of discussion and cooperation (Ayala, 2017). There is a need for this Agenda to turn into an institution.

The transboundary water situation in Central America is thus a particularly important issue regarding regional and national security. The nexus between risks and threats common to the region are therefore of great relevance when looking at the management of transboundary water resources. Such management is a non-negligible component of the peace and water security nexus and has to be addressed accordingly. The following section is developing the methodology in order to do so.

“Management of water as a service can lessen present and future water scarcity or contamination that would lead to corruption and insecurity”

03

Methodology

Through inductive research, this paper answers the following research question: What is the state of water cooperation in Central America? With the enabling factors developed by IGRAC and the TWINS model, we analyze the water interactions among countries in Central America to adapt existing tools and recommendations to this specific sub-regional hydro-security complex.

3.1. Factors Enabling Transboundary Aquifer Cooperation – the IGRAC Approach

We first used the eight factors developed by Conti in the IGRAC report and applied them to the 18 transboundary aquifers in this analysis. Based on a review of primary and secondary sources, we evaluated the number of existing enabling factors in each aquifer. The higher the number of enabling factors, the stronger the possibilities of enabling cooperation over transboundary groundwater. A further analysis of which factors were in general present or lacking in the region allowed us to draw some findings and recommendations.

To identify these enabling factors, our research team has created a data sheet for each of the 18 basins. The data sheets were primarily based on the data found in the UNESCO/OEA ISARM preliminary report (UNESCO/OEA/ISARM AMERICAS, 2007). The research team has then collected, processed and coded the data based on official documents and secondary sources, updating the data sheets and adding information for each of the enabling factors in the data sheet of each basin. If there was data suggesting the existence of one of the enabling factors, the research team would discuss and inform/confirm the enabling factor to ensure congruent coding within the team. The purpose of the research was to identify these enabling factors in the Central American case.

3.2. Transboundary Water Interactions – the TWINS Model

We then proceeded to the second part of the analysis through the TWINS model. This section describes how transboundary water management, be it surface or groundwater, often imply both cooperation and conflict among the different stakeholders (Mirumachi, 2015, Zeitoun & Mirumachi,, 2008). Here, "Transboundary Aquifer Interactions characterize the dynamics between aquifer states, including both cooperative and conflictive elements" (Conti, 2014, p. 10). The Transboundary Water Interactions NexuS (TWINS) model is employed to facilitate the understanding of these dynamics in each transboundary aquifer case in Central America analyzed in this paper.

In an article on the so-called 'cooperation versus conflict paradox', Zeitoun (2007) intended to explain the reasons behind conflict or cooperation perceptions about transboundary water management, saying that there is actually no existing paradox between the two. Reflecting on the co-existence of conflictual and cooperative events, Zeitoun argues that scholars have struggled to deal with this issue. With the TWINS model, Mirumachi & Allan (2007) address the duality of transboundary water interactions. The scholars analyze these interactions by positioning them on a two-dimensional matrix instead of placing them on a continuum with two opposite ends. With the analysis of both processes, their different levels, and a certain timeline, analysts can observe how these cooperative and conflictual interactions do not determine the overall water relations between two riparian actors, preventing them from being categorized between strict conflict or cooperation. Subsequent studies have added to the model over the years. Water interactions, in addition to being characterized by both conflict and cooperation processes (Mirumachi, 2015), are also the result of a combination of contest and compliance mechanisms (Zeitoun *et al*., 2017), influenced by negative forms of cooperation and positive forms of conflict (Zeitoun & Mirumachi, 2008; Swatuk, 2015). Soft power is an equally important element (Zeitoun *et al*., 2011), as well as the relevance of the different levels where these processes can happen (Warner, 2005; Julien, 2012; Norman, 2012; Conker, 2014).

TWINS helps shape the relative degrees of conflict and cooperation over hydraulic resources in a given political relationship. In a 3D schema by Mirumachi & Allan (2007), the vertical axis (y-axis) represents the different intensities of conflictual interactions, which go from low to violent interactions. The different categories in increasing levels of conflict in Mirumachi's scale are: non-politicized, politicized, securitized/ "opportunitized", and "violized". Cooperative interactions are situated on the horizontal axis (x-axis). Mirumachi has established the following increasing order for the different levels of cooperation: issue confrontation, ad hoc interaction, technical, risk-averting, and risk-taking. Due to independent categorization, levels of cooperation and conflict interactions can be happened simultaneously when looking at transboundary groundwater use and management. Cases characterized by low conflict and low cooperation, or on the contrary, with high cooperation and high conflict, can be identified (Conti, 2014, p. 12). A third dimension was added by Mirumachi & Allan (2007) to indicate the situation regarding the robustness of the political economy, ranging from resource capture, to resource sharing to development of resource alternatives. For the purpose of this paper, we applied a modified version from the original model developed by Mirumachi & Allan (2007). We then took water interactions between each riparian State as a whole instead of identifying co-existing cooperation and conflict in different periods over time for each basin.

"Due to independent categorization, levels of cooperation and conflict interactions can be happened simultaneously when looking at transboundary groundwater use and management"

04
Case Study

In this section, we analyze all of the 18 aquifers (see Annex I for a detailed table of each aquifer's main characteristics). The aquifers in Table 11-2 are first analyzed through the list of IGRAC's enabling factors, before being applied to the TWINS model for establishing transboundary water interactions.

Based on the analysis of data from primary sources such as official documents, statements and reports from the different governments and international organizations, as well as scientific articles and from secondary sources such as newspaper articles (see Annex 1), we established a table where the eight enabling factors were listed as present or lacking for each transboundary aquifer case. This approach allowed us to indicate which of these factors each aquifer did and did not have as summarized in Figure 11-3.

We then applied the modified TWINS model to the Central American transboundary aquifers. Again, we compiled data from primary sources such as official documents, statements and reports from the different governments and international organizations, as well as scientific articles. We also used secondary sources such as newspaper articles. Table 11-3 shows how the 18 basins are distributed across the nine possible configurations in the model.

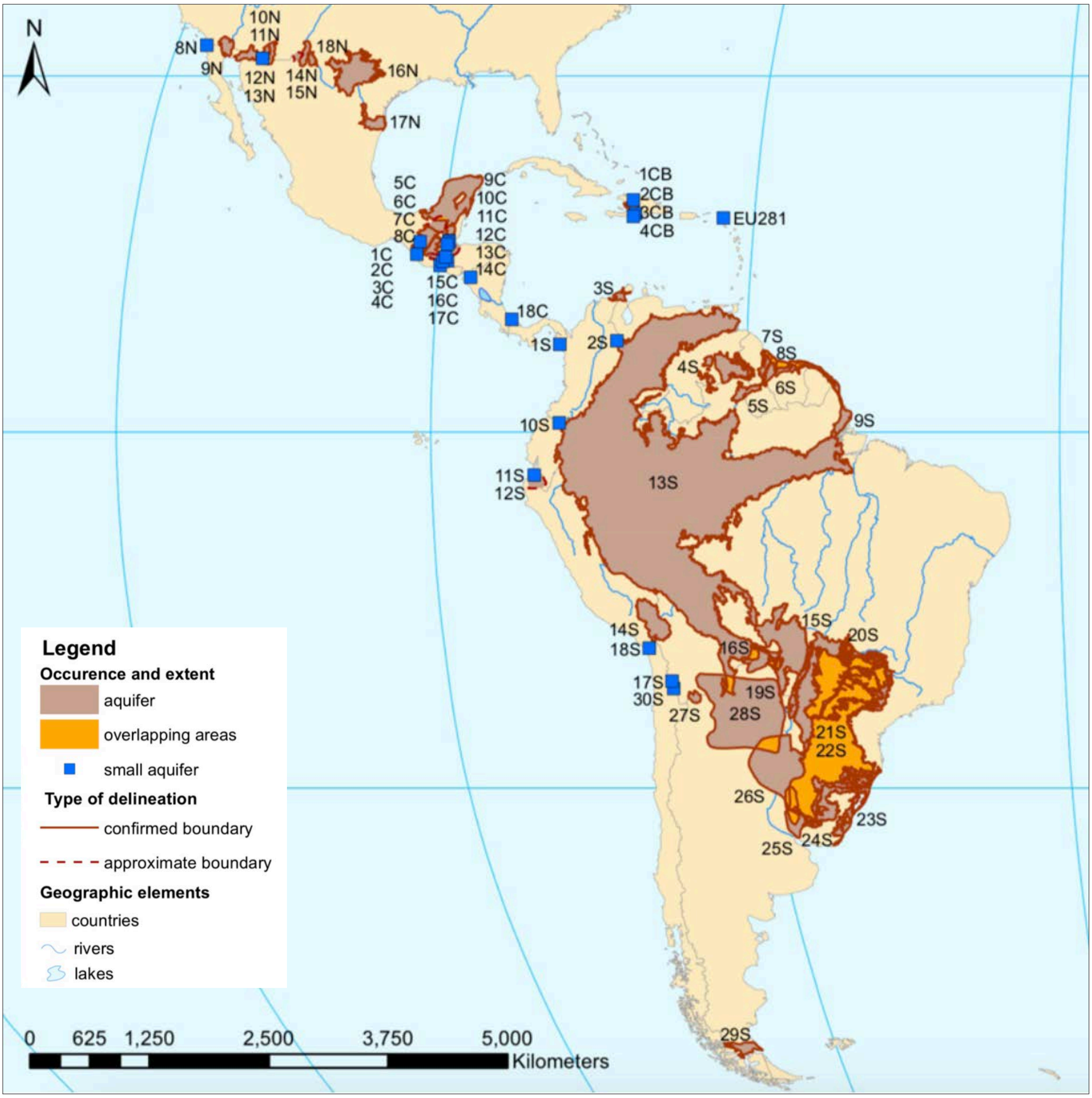


Figure 11-2 *Map of Latin American transboundary aquifers (Source: IGRAC, 2015). See Table 11-2 for the alpha-numeric codes*

Table 11-2 Transboundary aquifers in Central America (Source: IGRAC, 2015)

	Aquifer	States
1C	Soconusco-Suchiate/Coatán	Guatemala and Mexico
2C	Chicomuselo-Cuilco/Selegua	Guatemala and Mexico
3C	Ocosingo-Usumacinta-Pocom-Ixcan	Guatemala and Mexico
4C	Marquez de Comillas-Chixoand/Xacbal	Guatemala and Mexico
5C	Boca del Cerro-San Pedro	Guatemala and Mexico
6C	Trinitaria-Nenton	Guatemala and Mexico
7C	Yucatán Peninsula-Candeleria-Hondo	Guatemala, Belize and Mexico
8C	Mopán-Belize	Guatemala and Belize
9C	Pusila-Moho	Guatemala and Belize
10C	Sarstún	Guatemala and Belize
11C	Temash	Guatemala and Belize
12C	Motagua	Guatemala and Honduras
13C	Chiquimula-Copan Ruinas	Guatemala and Honduras
14C	Esquipulas-Ocotepeque-Citalá	Guatemala, Honduras and El Salvador
15C	Ostúa-Metapán	Guatemala and El Salvador
16C	Paz river	Guatemala and El Salvador
17C	Estero Real-Negro river	Honduras and Nicaragua
18C	Sixaola	Costa Rica and Panama

Summary of Enabling Factors Present by Transboundary Aquifer

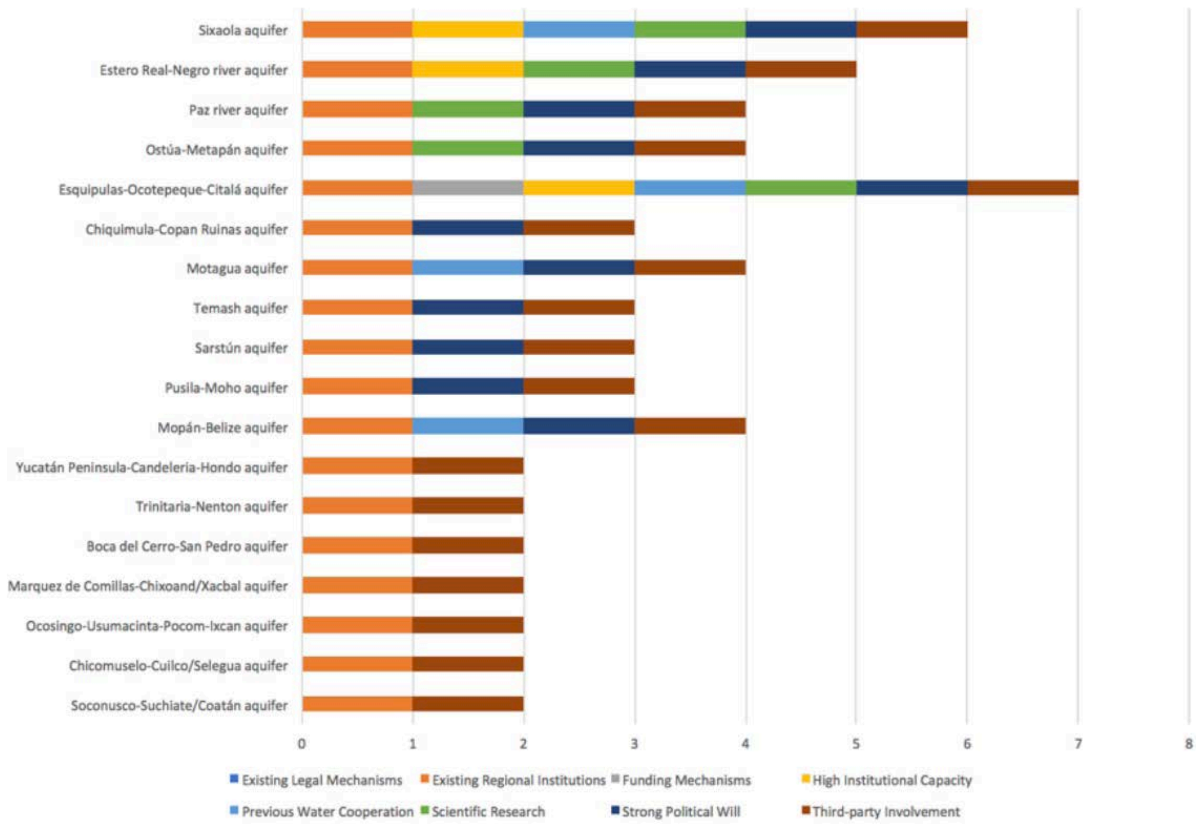


Figure 11-3 Summary of Transboundary Aquifer Interactions

Table 11-3 *Summary of Transboundary Aquifer Interactions*

	Low Cooperation	Moderate Cooperation	High Cooperation
Low Conflict	7	3	0
Moderate Conflict	6	2	0
High Conflict	0	0	0

In the case of Central America, there is still no interaction categorized by high cooperation nor high conflict.
The next section discusses the interplay between the enabling factors developed by Conti (2014) and the dynamic state of interactions between transboundary aquifer states developed around the TWINS model (Mirumachi & Allan, 2007; Mirumachi, 2015; Zeitoun *et al.*, 2011; Zeitoun *et al.*, 2017) that we just applied to our 18 transboundary aquifers cases.

05 Discussion

This section discusses the overall level of engagement (low, moderate and high engagement cases) between aquifer states for each case of transboundary aquifer cooperation. By doing so, the interplay indicates the overall situation specific to each aquifer case and to which extent enabling factors are present or missing, given the occurrence of cooperative Transboundary Aquifer (TBA) Interactions.
The combination is presented in summary tables. An overall summary with all transboundary aquifer basins can be found in Annex 2.

5.1. Low Engagement Cases

Low engagement cases refer to transboundary aquifer management cases where "(1) states previously engaged about the transboundary aquifer but those activities are dormant or (2) cooperative activities are nascent, ad-hoc and informal" (Conti, 2014, p. 35). Based on these criteria, we found 13 cases out of the 18 transboundary aquifer cases existing in Central America.

5.2. Moderate Engagement Cases

Moderate engagement cases referred to transboundary aquifer management cases if "(1) there is ongoing cooperation, but it is informal or occurring outside of a formal water management institution, (2) a formal water management institution has just begun or (3) formal cooperation has become limited and sporadic" (Conti, 2014, p. 36). Based on these criteria, 5 transboundary aquifer cases out of the existing 18 corresponded to this category.

5.3. High Engagement Cases

High engagement cases referred to transboundary aquifer management cases where "(1) there is ongoing cooperation in the context of a formal institution or (2) there is frequent ongoing cooperation in the context of a formal project" (Conti, 2014, p. 37). Based on these criteria, only 1 transboundary aquifer case out of the existing 18 corresponded to this category, the Esquipulas-Ocotepeque-Citalá aquifer.

These summary tables highlight how water interactions are matched with a certain number of enabling factors. Here, we observe that most of the aquifer basins with transboundary water interactions characterized by low cooperation and low or moderate conflict are the basins with a relatively small

Table 11-4 Summary of Low Engagement Cases

Aquifer Name	TBA Interaction			Enabling Factors Present				
	Low Cooperation	Moderate Conflict	Low Conflict	Regional Institution	Strong Political Will	Scientific Research	Previous Water Cooperation	Third-Party Involvement
Soconusco-Suchiate/Coatán	✓		✓	✓				✓
Chicomuselo-Cuilco/Selegua	✓		✓	✓				✓
Ocosingo-Usumacinta-Pocom-Ixcan	✓		✓	✓				✓
Guatemala	✓		✓	✓				✓
Honduras	✓		✓	✓				✓
Nicaragua	✓		✓	✓				✓
Panama	✓		✓	✓				✓
Marquez de Comillas-Chixoand/Xacbal	✓		✓	✓				✓
Boca del Cerro-San Pedro	✓		✓	✓				✓
Trinitaria-Nenton	✓		✓	✓				✓
Yucatán Peninsula-Candeleria-Hondo	✓		✓	✓				✓
Pusila-Moho	✓	✓		✓	✓			✓
Sarstún	✓	✓		✓	✓			✓
Temash	✓	✓		✓	✓			✓
Chiquimula-Copan Ruinas	✓	✓		✓	✓			✓
Ostúa-Metapán	✓	✓		✓	✓	✓		✓
Paz river	✓	✓		✓	✓	✓	✓	✓

Table 11-5 Summary of Moderate Engagement Cases

Aquifer Name	TBA Interaction			Enabling Factors Present					
	Moderate Cooperation	Low Conflict	Moderate Conflict	Regional Institution	High Institutional Capacity	Strong Political Will	Scientific Research	Previous Water Cooperation	Third-Party Involvement
Estero Real-Negro river	✓	✓		✓	✓	✓	✓		✓
Sixaola	✓	✓		✓	✓	✓	✓	✓	✓
Mopán-Belize	✓		✓	✓		✓		✓	✓
Motagua	✓		✓	✓		✓		✓	✓

Table 11-6 Summary of High Engagement Cases

Aquifer Name	TBA Interaction		Enabling Factors Present						
	Low Cooperation	Low Conflict	Regional Institution	Funding Mechanisms	Strong Political Will	Scientific Research	Previous Water Cooperation	Third-Party Involvement	High Institutional Capacity
Esquipulas-Ocotepeque-Citaláriver	✓	✓	✓	✓	✓	✓	✓	✓	✓

number of enabling factors. These form the low engagement cases. The aquifer basins in the moderate engagement cases are those which have transboundary water interactions marked by moderate cooperation and low or moderate conflict. These have a higher number of enabling factors. Finally, it is interesting to note that the high engagement cases are defined by a similar situation for transboundary water interactions as for moderate engagement cases: with moderate cooperation and low conflict. However, the number of existing enabling factors here is higher than in the previous category.

These tables also allow one to highlight the lack of certain specific enabling factors. According to our analysis, the common missing enabling factor in Central America is the legal mechanisms factor. It has been demonstrated before how transboundary groundwater, due to its invisibility, often leads to a lack of political will and capacity for joint management. Another interesting point when it comes to groundwater is the different legal system around water located in the ground compared to surface water. Moreover, the sovereignty issue is especially present when it comes to transboundary water. For instance, the 2008 UN draft articles on the Law of Transboundary Aquifers, adopted by the United Nations International Law Commission to deal specifically with transboundary groundwater, includes the sovereignty principle. On the contrary, the 1997 Watercourse Convention, an international treaty adopted by the General Assembly of the United Nations which sets biding principles regarding non-navigational uses of international waters, does not (Albrecht *et al*., 2017, p. 6). We argue that the sovereignty principle is especially present in Latin America. (Walschot, 2020). As a matter of fact, "Latin America has a long history in the juridical tradition of preserving national sovereignty, and also in the devising of special mechanisms to defend and enforce it, either in the domestic sphere, or through international law" (de Almeida, 2013). Funding mechanisms, scientific research and previous water cooperation are enabling factors that can be found in some of these transboundary aquifer cases, but are still lacking in many. They are often found where surface water is linked to the aquifer. This could cause prejudice to confined aquifers which are not part of a surface watershed. The enabling factor of institutional capacity is also problematic in the region, where only one State, Nicaragua, has implemented a national water law. From this analysis, we can therefore highlight how these main issues are particularly related to groundwater in Central America as a sub-regional hydro-security complex.

"An informal dialogue could lead to enhanced cooperation through the development of high political will and appropriate funding"

Based on our analysis on these sets of existing enabling factors in the different transboundary basins in Central America and on the particularity of the region as a sub-regional hydro-security complex, specific measures have to be taken in order to enhance transboundary groundwater management, peace and water security. According to Conti (2014, p. 41), "some Enabling Factors are more critical for certain levels of engagement. This finding can be instrumental in helping policy makers and practitioners increase the level of cooperation within their respective transboundary aquifers." Depending on the situation, institutions for the management of surface water or scientific research could initiate an informal dialogue even if there is no formal cooperation on groundwater. In other cases, an informal dialogue could lead to enhanced cooperation through the development of high political will and appropriate funding. In this case, the support of cooperative regional institutions such as the Organization of American States (OAS) or the Regional Committee on Hydraulic Resources emanating from the Central American Integration System (SICA/CRRH) has bolstered an existing but low-engagement situation in the region. Conti (2014) comes to the conclusion that this finding allows for the implementation of specific recommendations so that each enabling factor can enhance cooperation over transboundary aquifers. In the following section, we see how these main issues are reflected in the five recommendations formulated by Albrecht *et al*. (2017).

06

Policy Recommendations and Conclusions

In this section, we highlight the different policy implications stemming from our research. We then analyze existing tools and make recommendations on how to improve or innovate transboundary groundwater cooperation, before concluding the paper with our major findings. By the term tools, we mean the different methods and skills to approach water conflict transformation and ensure water security and peace. New tools would aim at the combination of analytical and process-oriented knowledge and skills to manage groundwater through a comprehensive approach at the regional, national and local levels, especially with the application of the hydro-security complex framework.

The fact that groundwater has different attributes and is exposed to different risks than surface water is coupled with the fact that aquifer properties are different between and within individual aquifers. Indeed, "due to this heterogeneity, different governance approaches may be needed for different groundwater systems" (Albrecht *et al.*, 2017:4; Jarvis, 2007, p. 181). Despite the fact that data are hard to obtain, especially in a transboundary context (Linton & Brooks, 2001), "characterizing aquifer properties is key to understanding how to sustainably manage groundwater resources. In transboundary contexts, shared aquifers are even more likely to be poorly understood and, therefore, mismanaged" (Albrecht *et al.*, 2017, p. 4).

"New tools would aim at the combination of analytical and process-oriented knowledge and skills to manage groundwater through a comprehensive approach at the regional, national and local levels, especially with the application of the hydro-security complex framework"

Studies have shown that some key elements are critical to ensure the sound management of transboundary groundwater, such as the engagement of all stakeholders; sharing data and knowledge; monitoring implementation (Garduño *et al.*, 2010; Konikow & Kendy, 2005; Rivera, 2015; Varady *et al.*, 2016; Walschot, 2020). After a review of the academic literature and official documents from governmental and international sources on the topic, we have chosen to base our recommendations on the 2017 study of Albrecht *et al.*, "Governing a shared hidden resource: A review of governance mechanisms for transboundary groundwater security".

Albrecht *et al.* (2017) developed a set of recommendations for governance mechanisms to enhance transboundary groundwater security. Developing on this work and based on our research, this paper adapts these improved governance recommendations to the specific context of Central America as a regional hydro-security complex.

Enhancing context-specific and flexible international mechanisms

Where Albrecht *et al.* (2017, p. 10) highlight that "flexible, adaptive mechanisms are needed to address complexities of the physical and ecological systems within which groundwater reserves lie", we add that these context-specific mechanisms have to understand the specificities, not only of each basin, but also of the regional hydro-security complex as a whole.

Addressing the ongoing need for groundwater data and information

Since "gathering sufficient information on groundwater systems can reduce uncertainty, and should be conducted prior to developing a specific legal framework" (Albrecht *et al.*, 2017, p. 10), we argue that the emphasis has to be put on a regional incentive, as it has previously proved to be effective with the OAS and SICA/CRRH, of sharing groundwater data and information.

Prioritizing the precautionary principle and pollution prevention

According to Albrecht *et al.* (2017, p. 10), "at the international level, the principle of equitable and reasonable use prioritizes current and historic uses over sustainable use." This is definitely an important issue to acknowledge in Central America and efforts have to be undertaken to prioritize these central principles amidst sovereignty and rights to use approaches.

Integrating governance with surface water, land, and subsurface management

The 'hydrological unity' recommended by Albrecht *et al.* (2017) is certainly of great importance, but has to be put back into the greater regional context, as is recommended in the TWINS model developed by Mirumachi *et al.* (2007) and is developed in our analysis of Central America as a sub-regional hydro-security complex.

Expanding institutional capacity

According to Albrecht *et al.* (2017, p. 12), "Locally-based, cross-border agreements, arranged between communities along international borders, may be appropriate and effective, particularly in cases where transboundary aquifers are limited in extent and garner little political attention from national-level governments." First, this is particularly relevant for Central America, as our paper has shown that strong political will, as an Enabling factor, is still lacking in almost all transboundary aquifer cases in the sub-region (see Figure 11-3). Second, this corroborates our statement on the fact that the mere existence of an international agreement is not sufficient, since the implementation phase, the participation of all stakeholders, especially at the local level, and the creation of a joint commission or institution are also crucial for sound transboundary water management (Hantke-Domas, 2011; Embid & Liber, 2015; Walschot, 2020). According to the GWP (2016, p. 17), "the reason for this is that enforcing the laws depends on how water planning is developed and implemented, what budgets are allocated, how institutions perform, and how the public's right to participate is exercised."

> *"Water can be a tool for peace if the right enabling factors, mechanisms and policies are put in place"*

According to Albrecht *et al.* (2017, p. 12), "modern, progressive, global water initiatives offer new opportunities for revised thinking and more suitable approaches. These provide a growing role for new and more broadly representative actors and institutions, fresh perspectives, innovative paradigms, and effective strategies for promoting secure access to and use of shared groundwater resources."

New or improved ways of managing transboundary water are therefore needed. What this paper has highlighted is the necessity of considering the integration of governance with surface water, land, and subsurface management, as well as the integration of this management within the regional or sub-regional hydro-security complex.

In conclusion, water can be a tool for peace if the right enabling factors, mechanisms and policies are put in place. Moreover, it is essential to incorporate all actors as early in the cooperation/negotiation process as possible.
In a region such as Central America where violence and conflicts are present, it is critical to ensure sound governance of transboundary groundwater, considering the region or sub-region from a comprehensive point of view. Ensuring water security is securing a path to peace, or at least away from more conflict. When considering water as threat multiplier, one needs to turn it into a cooperative tool.

What is offered here is a preliminary study on the issue of transboundary aquifers management in Central America and water security. In-depth research on the ground is needed, which would allow special attention to be given to certain variables, such as gender, poverty, and the effects of climate change on aquifer recharge, among other topics, which are also critical to develop sound management of transboundary water resources. A comprehensive analysis of the complex issues would require additional information. The lack of information available, due partly to the fact that these cases have attracted less attention as others, and data on transboundary aquifers is still scarce, limit the analysis that can be completed at this time.

References

Abukhater, A. (2013). *Water as a catalyst for peace: transboundary water management and conflict resolution*. Routledge.

Alam, M. J. B., Islam, M. R., Muyen, Z., Mamun, M. & Islam, S. (2007). Water quality parameters along rivers. *International Journal of Environmental Science & Technology*, 4, pp. 159–167. https://doi.org/10.1007/BF03325974.

Albrecht, T. R., Varady, R. G., Zuniga-Teran, A. A., Gerlak, A. K. & Staddon, C. (2017). Governing a shared hidden resource: A review of governance mechanisms for transboundary groundwater security. *Water Security, 2*, pp. 43-56.

Ale, S., Omani, N., Himanshu, S. K., Bordovsky, J. P., Thorp, K. R. & Barnes, E. M. (2020). Determining optimum irrigation termination periods for cotton production in the Texas High Plains. *Transaction in ASABE*, 63(1), pp. 105-115.

Aviram, R., Katz, D. & Shmueli, D. (2014). Desalination as a game-changer in transboundary hydro-politics. *Water Policy, 16*(4), pp. 609–624.

Ayala, E. (2017, December 2017). Central America Hashes Out Agenda for Sustainable Use of Water. *IPS – Inter Press Service*. http://www.ipsnews.net/2017/12/central-america-hashes-agenda-sustainable-use-water/?utm_source=rss&utm_medium=rss&utm_campaign=central-america-hashes-agenda-sustainable-use-water.

Bakker, K. (2012). Water Security: Research Challenges and Opportunities. *Science*, 337(6097), pp. 914–915. https://doi.org/10.1126/science.1226337.

Beisheim, M. (ed.). (2013). Der Nexus Wasser-Energie-Nahrung. Wie mit vernetzten Versorgungsrisiken umgehen? [The water, energy & food security nexus: How to govern complex risks to sustainable supply?]. *Stiftung Wissenschaft und Politik* (Issue 11).

Burchi, S. (2018). Legal frameworks for the governance of international transboundary aquifers: Pre- and post-ISARM experience. *Journal of Hydrology: Regional Studies*, 20, pp. 15-20.

CEPAL. (2015). *Cambio climático en Centroamérica – Impactos potenciales y opciones de política pública*. LC/MEX/L.1196. United Nations.

Çonker, A. (2014). An enhanced notion of power for inter-state and transnational hydropolitics: An analysis of Turkish-Syrian water relations and the Ilisu Dam. Ph.D. thesis submitted to the School of International Development. University of East Anglia.

Conti, K. I. (2014). *Factors Enabling Transboundary Aquifer Cooperation: A Global Analysis*. International Groundwater Resources Assessment Centre.

Craig, J. G. (1993). *The Nature of Co-operation*. Black Rose Books.

de Almeida, P. R. (2013). Sovereignty and regional integration in Latin America: a political conundrum? *Contexto internacional*, 35(2). http://dx.doi.org/10.1590/S0102-85292013000200006.

Embid, A. & Liber, M. (2015). *La experiencia legislativa del decenio 2005-2015 en materia de aguas en América Latina*. CEPAL.

Eckstein, Y. & Eckstein, G. E. (2005). Transboundary aquifers: conceptual models for development of international law. *Ground Water*, 3(5), pp. 679–690.

FAO AQUASTAT2. (n.d.). Retrieved July 14, 2020, from www.fao.org/nr/water/aquastat/data.

Garduño, H., van Steenbergen, F. & Foster, S. (2010). Stakeholder participation in groundwater management, *GW Mate Briefing Note Series*.

Gleick, P. H. (1993). Water and conflict: fresh water resources and international security. *International Security*, 18, pp. 79–112.

Grey, D. & Sadoff, C. W. (2007). Sink or swim? Water security for growth and development. *Water Policy*, 9(6), pp. 545–571.

Guasch, L. & Straub, S. (2009). Corruption and concession renegotiations: Evidence from the water and transport sectors in Latin America. *Utilities Policy*, 17(2), pp. 185-190.

GWP. (2016). *In Integrated water resources management in Central America: the over-riding challenge of managing transboundary waters*. Global Water Partnership.

Hantke-Domas, M. (2011). *Avances legislativos en gestión sostenible y descentralizada del agua en América Latina*. CEPAL.

Hatch Kuri, G. (2018). A Joint Management of Transboundary Aquifers: From Asymmetries to Environmental Protection. Frontera Norte, 30 (59), pp. 129-154.

Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I., Diedhiou, A., Djalante, R., Ebi, K. L., Engelbrecht, F., Guiot, J., Hijioka, Y., Mehrotra, S., Payne, A., Seneviratne, S. I., Thomas, A., Warren, R. & Zhou, G. (2018) Impacts of 1.5ºC Global Warming on Natural and Human Systems. In Masson-Delmotte, V., Zhai, P., Pörtner, H. O., Roberts, D., Skea, J., Shukla, P. R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J. B. R., Chen, Y., Zhou, X., Gomis, M. I., Lonnoy, E., Maycock, T., Tignor, M. & Waterfield, T. (eds.) *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. In Press.

Hoekstra, A. Y., Buurman, J. & Ginkel, K. C. H. van. (2018). Urban water security: A review. *Environmental Research Letters*, 13(5), 053002. https://doi.org/10.1088/1748-9326/aaba52.

ILEC, UNEP-DHI, UNESCO-IHP, UNESCO-IOC & UNEP. (2016). Water System Information Sheets: Central America and Caribbean. In Talaue-McManus, L. (ed) *Transboundary Waters: A Global Compendium,6*-Annex B. United Nations Environment Programme (UNEP).

IGRAC (International Groundwater Resources Assessment Centre) & UNESCO-IHP (UNESCO International Hydrological Programme). (2015). Transboundary Aquifers of Latin America. Based on: Transboundary Aquifers of the World [map]. Edition 2015. Delft, Netherlands: IGRAC, 2015.

INBO & GWP. (2012). The handbook for integrated water resources management in transboundary basins of rivers, lakes and aquifers. International Network of Basin Organizations (INBO) and the Global Water Partnership (GWP).

Jarvis, W. T. (2007). *Transboundary groundwater: geopolitical consequences, common sense, and the law of the Hidden Sea* (ProQuest Dissertations and These).

Jensen, O. & Wu, H. (2018). Urban water security indicators: Development and pilot. *Environmental Science & Policy*, 83, pp. 33–45. https://doi.org/10.1016/j.envsci.2018.02.003.

Jepson, W., Budds, J., Eichelberger, L., Harris, L., Norman, E., O'Reilly, K., Pearson, A., Shah, S., Shinn, J., Staddon, C., Stoler, J., Wutich, A. & Young, S. (2017). Advancing human capabilities for water security: A relational approach. *Water Security*, 1, pp. 46-52. https://doi.org/10.1016/j.wasec.2017.07.001.

Jiménez, A., Saikia, P., Giné, R., Avello, P., Leten, J., Lymer, B.L., Schneider, K. & Ward, R. (2020). Unpacking Water Governance: A Framework for Practitioners. *Water*,12(827), pp. 1-21.

Julien, F. (2012). Hydropolitics is what societies make of it (or why we need a constructivist approach to the geopolitics of water). *International Journal of Sustainable Society*, 4(1/2), pp. 45–71.

Konikow, L. F. & Kendy, E. (2005). Groundwater depletion: a global problem. *Hydrogeological Journal*, 13(1), pp. 317–320.

Koop, S. H. A. & van Leeuwen, C. J. (2015). Assessment of the Sustainability of Water Resources Management: A Critical Review of the City Blueprint Approach. *Water Resources Management*, 29(15), pp. 5649–5670. https://doi.org/10.1007/s11269-015-1139-z.

Leite, M. L. T. de A. & Ribeiro, W. C. (2018). The Guarani Aquifer System (Gas) and the Challenges for Its Management. *Journal of Water Resource and Protection*, 10, pp. 1222-1241.

Linton, J. & Brooks, D. (2001). Governance of transboundary aquifers: New challenges and new opportunities. *Water International*, 36, pp. 606-618.

Mirumachi, N. & Allan, J. A. (2007). *Revisiting Transboundary Water Governance: Power, Conflict, Cooperation and the Political Economy*, CAIWA Conference Paper.

Mirumachi, N. (2015). *Transboundary water politics in the developing world*. London: Routledge.

Moreno-Sainz, M. L. (2017). *New Trends in 2 Regional Security Complexes: Adapting to the New Security Challenges*. Geneva Center for Security Policy. HAL-archives hal-01599158.

Norman, E. S. (2012). Cultural politics and transboundary resource governance in the Salish Sea. *Water Alternatives*, 5(1), pp. 138–160.

Pahl-Wostl, C., Lebel, L., Knieper, C. & Nikitina, E. (2012). From applying panaceas to mastering complexity: Toward adaptive water governance in river basins. *Environmental Science & Policy*, 23, pp. 24–34. https://doi.org/10.1016/j.envsci.2012.07.014.

Petersen-Perlman, J. D., Veilleux, J. C. & Wolf, A. T. (2017). International water conflict and cooperation: challenges and opportunities. *Water International*, 42(2), pp. 105-120.

Pion-Berlin, D. & Trinkunes, H. (2011). Latin America's growing security gap. *Journal of Democracy*, 22(1), pp. 39-53.

Plummer, J. (2008). Introducing water and corruption. In Transparency International, *Global Corruption Report 2008. Corruption in the Water Sector*, Cambridge University Press, 3-15.

Ribeiro, W. C. (2008) *Geografia política da água*. São Paulo : Annablume.

Ribeiro, W. C. & Sant'Anna, F. M. (2014). Water security and interstate conflict and cooperation. *Documents D'Anàlisi Geogràfica [s.l.]*, 60(3), pp. 573–596.

Rivera, A. (2015). Transboundary aquifers along the Canada-USA border: science, policy and social issues. *Journal of Hydrology: Regional Studies*, 4, pp. 623–643.

Ruhl, J. M. (2011). Political Corruption in Central America: Assessment and Explanation. *Latin American Politics and Society*, 53(1), pp. 33-58.

Sadoff, C., Grey, D. & Borgomeo, E. (2020, May 29). Water Security. *Oxford Research Encyclopedia of Environmental Science*. Retrieved 26 Jul. 2020, from https://oxfordre.com/environmentalscience/view/10.1093/acrefore/9780199389414.001.0001/acrefore-9780199389414-e-609.

Sindico, F. (2019). The Ocotepeque – Citalá Statement of Intent: a first step towards transboundary aquifer cooperation in Central America?, International Water Law Project. https://www.internationalwaterlaw.org/blog/2019/11/01/the-ocotepeque-citala-statement-of-intent-a-first-step-towards-transboundary-aquifer-cooperation-in-central-america/.

Sivapalan, M., Savenije, H. H. G. & Blöschl, G. (2012). Socio-hydrology: A new science of people and water. *Hydrological Processes*, 26(8), pp. 1270–1276. https://doi.org/10.1002/hyp.8426.

Srinivasan, V. (2013). Coevolution of water security in a developing city. *Hydrology and Earth System Sciences Discussions*, 10(11), pp. 13265–13291. https://doi.org/10.5194/hessd-10-13265-2013.

Swatuk, L. A. (2015). Water conflict and cooperation in Southern Africa. *WIREs Water.*

UNDP. (2014). *Informe sobre Desarrollo Humano 2014 Sostener el Progreso Humano: Reducir vulnerabilidades y construir resiliencia*. United Nations.

UNESCO/OEA/ISARM AMERICAS. (2007). *Sistemas Acuíferos Transfronterizos en las Américas. Evaluación Preliminar*. UNESCO.

van Leeuwen, C. J., Frijns, J., van Wezel, A. & van de Ven, F. H. M. (2012). City Blueprints: 24 Indicators to Assess the Sustainability of the Urban Water Cycle. *Water Resources Management*, 26(8), pp. 2177–2197. https://doi.org/10.1007/s11269-012-0009-1.

Varady, R. G., Zuniga-Teran, A. A., Gerlak, A. K. & Megdal, S. B. (2016). Modes and approaches of groundwater governance: a survey of lessons learned from selected cases across the globe. *Water*, 8(417), pp. 1–24. (In special issue, ''Water Governance, Stakeholder Engagement, and Sustainable Water Resources Management," ed. by S. Megdal, S. Eden, and E. Shamir).

Villar, P. C., Ribeiro, W. C., Sant'Anna, F. M. (2018). Transboundary governance in the La Plata River basin: status and prospects. *Water International*, 43(7), pp. 978-995.

Villar, P. C. & Ribeiro, W. C. (2011). The Agreement on the Guarani Aquifer: a new paradigm for transboundary groundwater management? *Water International*, 36(5), pp. 646-660.

Walschot, M. (2020). Hidro-diplomacia y soberanía nacional en el acuífero guaraní: ¿fracaso de un intento de gestión transfronteriza por intereses geopolíticos divergentes? *Agua Y Territorio*, 15, pp. 21-34.

Warner, J. (2005). *Hydro-hegemony as a layered cake: Hydro-hegemonic strategies in the case of Turkey*. Presentation given at First Workshop on Hydro-Hegemony, 21/22 May 2005, King's College London, London, UK, London Water Research Group.

Wolf, A. T. (2007). Shared Waters: Conflict and Cooperation. *Annual Review of Environment and Resources*, 32, pp. 241-269.

______. (2008). Healing the enlightenment rift: Rationality, spirituality, and shared waters. *International Affairs*, 61(2), pp. 51-73.

Zeitoun, M. (2007). The conflict vs. cooperation paradox: Fighting over or sharing of Palestinian-Israeli groundwater? *Water International, 32*(1), pp. 105–120.

______. (2011). The Global Web of National Water Security. *Global Policy, 2*(3), pp. 286–296. https://doi.org/10.1111/j.1758-5899.2011.00097.x.

Zeitoun, M. & Mirumachi, N. (2008). Transboundary water interaction I: reconsidering conflict and cooperation. *International Environmental Agreements*, 8, pp. 297–316.

Zeitoun, M., Mirumachi, N. & Warner, J. (2011). Transboundary water interaction II: Soft power under- lying conflict and cooperation. *International Environmental Agreements*, 11(2), pp. 159–178.

Zeitoun, M., Cascão, A. E., Warner, J., Mirumachi, N., Matthews, N., Menga, F. & Farnum, R. (2016). Transboundary water interaction III: contest and compliance. *International Environmental Agreements: Politics Law and Economics*, 17, pp. 271–294.

Notes

1. The 2019 Human Development Index does not provide figures for the freshwater withdrawals for Guatemala, Belize, El Salvador and Honduras. These figures match with the GWP figures for 2016, except for El Salvador which would be located among the middle third countries according to the UNDP classification.
2. The dependency ratio indicates the percentage of the total renewable water resources originating outside the country
3. 2. The Agenda was signed in 2017 by all Central American countries, plus the Dominican Republic.

12

Towards Improved Governance of Transboundary Aquifers in Southern Africa

A Synthesis on the Development and Operationalization of the Stampriet Transboundary Aquifer System (STAS) Cooperation Mechanism

Piet K. Kenabatho, Thato S. Setloboko, Bertram Swartz, Maria Amakali, Kwazikwakhe Majola, Ramogale Sekwele, Rapule Pule, Michael Ramaano, Koen Virbist and Alice Aureli

Piet K. Kenabatho, Department of Environmental Science, University of Botswana, Botswana. e-mail: kenabatho@ub.ac.bw
Thato S. Setloboko, Department of Water and Sanitation, Gaborone, Botswana. e-mail: tssetloboko@gov.bw
Bertram Swartz, Department of Water Affairs and Forestry, Windhoek, Namibia. e-mail: Bertram.Swartz@mawf.gov.na
Maria Amakali, Department of Water Affairs and Forestry, Windhoek, Namibia. e-mail: Maria.Amakali@mawf.gov.na
Kwazikwakhe Majola, Department of Water and Sanitation, Pretoria, South Africa. e-mail: majolak@dws.gov.za
Ramogale Sekwele, Department of Water and Sanitation, Pretoria, South Africa. e-mail: sekweler@dws.gov.za
Rapule Pule, ORASECOM Secretariat, Gauteng, South Africa. e-mail: rapule.pule@orasecom.org
Michael Ramaano, ORASECOM Secretariat, Gauteng, South Africa. e-mail: mike.ramaano@orasecom.org
Koen Virbist, UNESCO Regional Office for Southern Africa (ROSA), Harare, Zimbabwe. e-mail: .verbist@unesco.org
Alice Aureli, Groundwater Systems and Settlements Section UNESCO-IHP, Paris, France. e-mail: a.aureli@unesco.org

Abstract

The Stampriet Transboundary Aquifer System (STAS) is the only permanent and dependable water resource for the local population living in an 87,000 km^2 area from central Namibia into western Botswana and South Africa's Northern Cape Province. Understanding and managing this precious groundwater resource sustainably is essential to achieving water security and improvement of people's livelihood in this region. Consequently, the governments of these three countries, jointly with the UNESCO's Intergovernmental Hydrological Programme (UNESCO-IHP) and the Swiss Agency for Development and Cooperation (SDC) started an in-depth multi-disciplinary assessment of the aquifer in 2013. Insights from scientific results about the opportunities presented by STAS, led the three governments to decide on establishing a groundwater governance mechanism (the Multi-Country Cooperation Mechanism (MCCM)) for the joint governance and management of the aquifer by nesting it in the Orange-Senqu River basin Commission (ORASECOM). This becomes the first example of institutionalizing cooperation of a transboundary aquifer in Southern Africa to ensure continuous consideration of STAS specific priority issues beyond the project life. This paper presents the process leading to the establishment of the MCCM, some key achievements are also highlighted, as well as sharing the lessons learned during the implementation of UNESCO's Governance of Groundwater Resources in Transboundary Aquifers (GGRETA) project.

Keywords

Groundwater governance, Transboundary aquifers, river basin, ORASECOM, Stampriet Transboundary Aquifer System (STAS), Cooperation

01

Introduction

Groundwater is the primary source of water in many African countries and it is estimated that about 75% of the African population relies on groundwater, especially in rural communities (ECA *et al*., 2000; Braune & Xu, 2008; Nijsten *et al*., 2018). However, despite its strategic role in people's livelihood, groundwater in Africa is poorly understood and managed (BGR *et al*., 2007; Braune & Xu, 2008). Consequently, governance of this vital natural resource is compromised particularly at the transboundary level (Puri & Aureli, 2005). Over the years, transboundary water resource assessment and management have largely focused on surface water/river basins, and less on transboundary aquifer (TBA) assessment and management. This is despite the fact that there are seventy-two TBAs underlying 42% of the African continent which have already been mapped (IGRAC & UNESCO-IHP, 2015). Of these 72 TBAs, only eleven (i.e. 15%) have been subject of detailed scientific studies (Nijsten *et al*., 2018). Furthermore, cooperation relating to groundwater governance has been formalised for seven TBAs, mainly located in North Africa and the Sahel (Nijsten *et al*., 2018). In southern Africa, there are 34 known TBAs (IGRAC & UNESCO-IHP, 2015; Nijsten *et al*., 2018), where the Stampriet Transboundary Aquifer System (STAS) is the only TBA for which a cooperation mechanism has been established (ORASECOM, 2017). Since this development, other TBAs in the Southern African Development Community (SADC) region have recently been subject of detailed studies aimed at establishing groundwater governance mechanisms (Altchenko *et al*., 2017; Ebrahim *et al*., 2019; SADC-GMI, 2020).

> *“Transboundary water resource assessment and management have largely focused on surface water/river basins, and less on transboundary aquifer assessment and management”*

It is against this background that the success story of the STAS is shared with the international community in order to inspire other countries sharing TBAs to invest in the process of establishing cooperation mechanisms to ensure that transboundary groundwater management is given the highest priority, particularly in water stressed countries in Africa and beyond. This is because, according to the United Nations Water Organisation, adaptation to climate change and achievement of sustainable development goals is mainly possible through better water resources management strategies. As such, effective groundwater management strategies are necessary to increase its resilience towards climate variability and change (Cuthbert *et al*., 2019).

02

Background

2.1. A brief on Groundwater Governance and Groundwater Resources Management

There are many definitions of groundwater governance in the literature (Varady *et al*., 2013); one that is widely used and adopted for this paper is from Saunier and Meganck (2007), who define groundwater governance as ‘the process by which groundwater is managed through the application of responsibility, participation, information availability, transparency, custom and rule of law. It is the art of coordinating administrative actions and decision making between and among different jurisdictional levels – one of which may be global’. Some key words stand out from this definition, i.e. process, management, responsibility, participation, information, transparency, legislation, administration and institutions. These attributes suggest that groundwater governance advocates for a long-term arrangement that is carefully established through a consultative, transparent and participatory approach to effectively and efficiently monitor and manage groundwater resources to achieve water security. This needs to be institutionalised within a robust, credible, and high-level institution which is supported by legislation and enjoys the full trust and support of the participating member states in the case of transboundary aquifers (Foster *et al*., 2010). As suggested by Theesfeld (2010), governance structures are the organisational solutions for making rules effective, and are necessary for guaranteeing rights and duties and their implementation when making transactions. In the end, groundwater governance is also viewed as a vehicle to promote responsible collective action to ensure socially-sustainable utilisation and effective protection of groundwater resources for the benefit of humankind and dependent ecosystems (Foster & Garduño, 2013).

The science of groundwater is another crucial aspect for groundwater governance. It has been recognised that a lack of scientific and technical knowledge about specific transboundary or national aquifers is one of the major challenges to proper groundwater governance (IGRAC, https://www.un-igrac.org). Key scientific aspects of transboundary aquifers include knowledge of aquifer system boundaries which have been delineated based on sound hydrogeological properties such as lithostratigraphy, tectonics, regional piezometry, topography, among others. However in most cases, this information is not always available in most TBAs, or, where it exists, it is either of poor quality or inaccessible (UNESCO-IHP & IGRAC, 2016; SADC-GMI, 2020). Furthermore, environmental and socio-economic dynamics, legal and institutional arrangements, as well as gender considerations, need to be well understood to inform a potential groundwater cooperation mechanism. These multi-faceted and multi-disciplinary scientific studies were the cornerstones that informed the establishment of the cooperation mechanism of the Stampriet Transboundary Aquifer System (STAS) in southern Africa (UNESCO-IHP & IGRAC, 2016) which is part of the UNESCO project on Governance of Groundwater Resources in Transboundary Aquifers (GGRETA) that aims to enhance cooperation on water security, prevent transboundary and water-use conflicts, and improve overall environmental sustainability (UNESCO-IHP, 2016).

2.2. The Governance of Groundwater Resources in Transboundary Aquifers (GGRETA) Project

The GGRETA project is a UNESCO three-phased demonstration project that operates in three pilot transboundary aquifers, the Esquipulas-Ocotepeque-Citalá (Trifinio) Aquifer shared between El Salvador, Guatemala, and Honduras, the Stampriet Transboundary Aquifer System shared by Botswana, Namibia and South Africa, and the Pretashkent Aquifer shared between Kazakhstan and Uzbekistan. These aquifers represent different natural and socio-economic settings and are located in regions of potential conflicts over water among countries, among uses, and among users. It is a technical assistance effort that strives to achieve a better integration of groundwater resources into the water budget of basins, countries and regions, as part of a step-by-step approach to enable and foster transboundary cooperation. UNESCO's Intergavernmental Hydrological Programme (IHP) has embarked on this project, financed by the Swiss Agency for Development and Cooperation (SDC). For the Stampriet Transboundary Aquifer System (STAS), Phase I (2013-2015) involved in-depth assessment of the STAS focusing on hydrogeology, socio-economic and environmental components, legal and institutional components, and gender considerations. As discussed in Section 3, from the hydrogeological perspective, this phase sought to define, among others, the system boundaries and aquifer extent, main aquifers of the STAS, and the status of groundwater (quality, quantity and regional groundwater flow), as discussed in Section 3. For the socio-economic and environmental components, the project addressed issues of groundwater use (and land use) in the area, level of sanitation, and pollution sources. For the legal and institutional components, researchers sought to document and review the existing domestic laws/legislation and institutions used to manage groundwater in each of the three STAS countries, as regional legislations/frameworks in the SADC region. The gender component is aimed at documenting the degree of gender consideration in the management of groundwater in the STAS.

Phase II (2016-2019) involved capacity-building modules on groundwater modeling, legal and institutional, and gender issues, development of the STAS numerical model, and setting the baseline for institutionalizing cooperation over the STAS. Phase III (2020-2021) seeks to achieve key targets on reforming/updating legal, policy and institutional arrangements, strengthening capacity and implementing collective measures at national and regional levels to develop sustainable management and governance of transboundary aquifers and associated ecosystems. For more information, the reader is referred to the UNESCO-IHP's groundwater portal (https://groundwaterportal.net/ggreta). The purpose of this paper is to present the process leading to the establishment of the groundwater governance mechanism and the lessons learned using a case study of the Stampriet Transboundary Aquifer System (STAS), which is the first example of institutionalizing cooperation of a transboundary aquifer in Southern Africa.

03

A Case Study

3.1. The Stampriet Transboundary Aquifer System (STAS)

According to UNESCO and IGRAC (2016), the Stampriet Transboundary Aquifer System (STAS) is the only reliable and long term water resource for the local population living in an area from central Namibia into western Botswana and South Africa's Northern Cape Province (Figure 12-1). It lies entirely within the Orange-Senqu River Basin, covering a total area of 86,647 km^2 (73% of the area is in Namibia, 19% in Botswana, and 8% in South Africa). It is a large farming area with approximately 1,200 farms (mostly in Namibia), out of which 80 are irrigated farms.

Groundwater use is accounted for mainly by irrigation (about 52%), livestock watering (32%) and domestic water use (16%) (UNESCO & IGRAC, 2016). Currently, no mining or industrial activities are taking place in the area. The area is lightly populated, with approximately 50,000 inhabitants (UNESCO & IGRAC, 2016). Annual groundwater abstraction is about 20 Mm^3, with around 70% produced from the Stampriet town in Namibia.

Figure 12-1 *Location of the Stampriet Aquifer System (STAS)*

3.2. The Process for the Establishment of a Cooperation Mechanism

3.2.1. Derailed scientific studies and major findings

Through the coordination of UNESCO-IHP, detailed scientific assessment was carried out during the first phase of the GGRETA project- 2013-2015 (UNESCO & IGRAC, 2016). The assessment of the STAS was based on a multi-disciplinary methodology developed by UNESCO-IHP and the International Groundwater Resources Centre (IGRAC) that includes the collection and processing of national data (hydrogeological, socio-economic and environmental, gender, legal and institutional), and the harmonization of data across all three countries to enable a joint assessment of the transboundary resource (Figure 12-2).

Based on the data collected, analyzed and harmonized by national experts, a borehole database was established with information on more than 10 attributes for approximately 6,000 boreholes. This database is considered the cornerstone for the assessment, as it allowed the preparation of more than 40 thematic maps providing information on groundwater levels, borehole yield, geochemistry, and groundwater quality of the aquifer system (UNESCO-IHP & IGRAC, 2016). The thematic maps are available and can be visualized in the ORASECOM Information system (http://wis.orasecom.org/stas/).

Major findings from Phase I:

Hydrogeological and environmental components:

Three main aquifers have been identified in the STAS area (UNESCO & IGRAC, 2016), starting with the top predominantly phreatic local Kalahari aquifers which consist of discontinuous permeable zones in the Kalahari sediments. The Kalahari aquifers are the most intensively used aquifers within the STAS area, with their thickness varying from 0 to 350 m. The transmissivity values range between 0.1 m^2/d (STAS south-east area), 6 m^2/d (STAS central area), and 30 m^2/d (STAS south-west area) (UNESCO-IHP, 2016). Recharge to the Kalahari aquifers within the STAS area is generally restricted only to precipitation, which is estimated at 0.5% of rainfall (i.e. 0.7 to 1.5 mm/year) during the years with average rainfall, indicating that a substantial proportion of rainfall directly evaporates and consequently does not recharge the aquifers (JICA, 2002). The presence of large amounts of alien invasive species and other vegetation (e.g. prosopis) exacerbate groundwater loss in the area (UNESCO & IGRAC, 2016).

Below the Kalahari aquifers, and separated from them by aquitards, are the two confined Ecca group sandstones aquifers of Auob and Nossob, respectively, which together form the so-called Stampriet Artesian Basin. The lithostratigraphy and hydrogeologic units of the STAS are summarized in Table 12-1 (UNESCO & IGRAC, 2016). Hydraulic connection between the unconfined Kalahari aquifers and the confined Auob aquifer might exist through geological faults, but most likely also by slow seepage/leakage through aquitards, in spite of their very low permeability (van Wyk, 2014).

The Auob aquifer can be found at depths varying from 0 to over 300 m, with thickness ranging between 0 and 150 m, while the Nossob aquifer may extend to more than 400 m below the ground, with thickness varying from 0 to 60 m in Namibia, and from 0 to 20 in South Africa. The transmissivity values for the Auob and Nossob are much higher than those of the Kalahari aquifers, ranging between 0.1 to 200 m^2/d, with maximum values going up to 1,240 m^2/d (STAS north-west area) for the Auob, and between 0.1 and 100 m^2/d for the Nossob, with maximum values of up to 1,480 m^2/d (STAS central area) (UNESCO-IHP, 2015).

Recharge to the Auob and Nossob aquifers during normal rainfall years is considered non-existent. The main recharge mechanisms to the Auob aquifer are through: (i) diffuse recharge by downward seepage from the Kalahari aquifer;

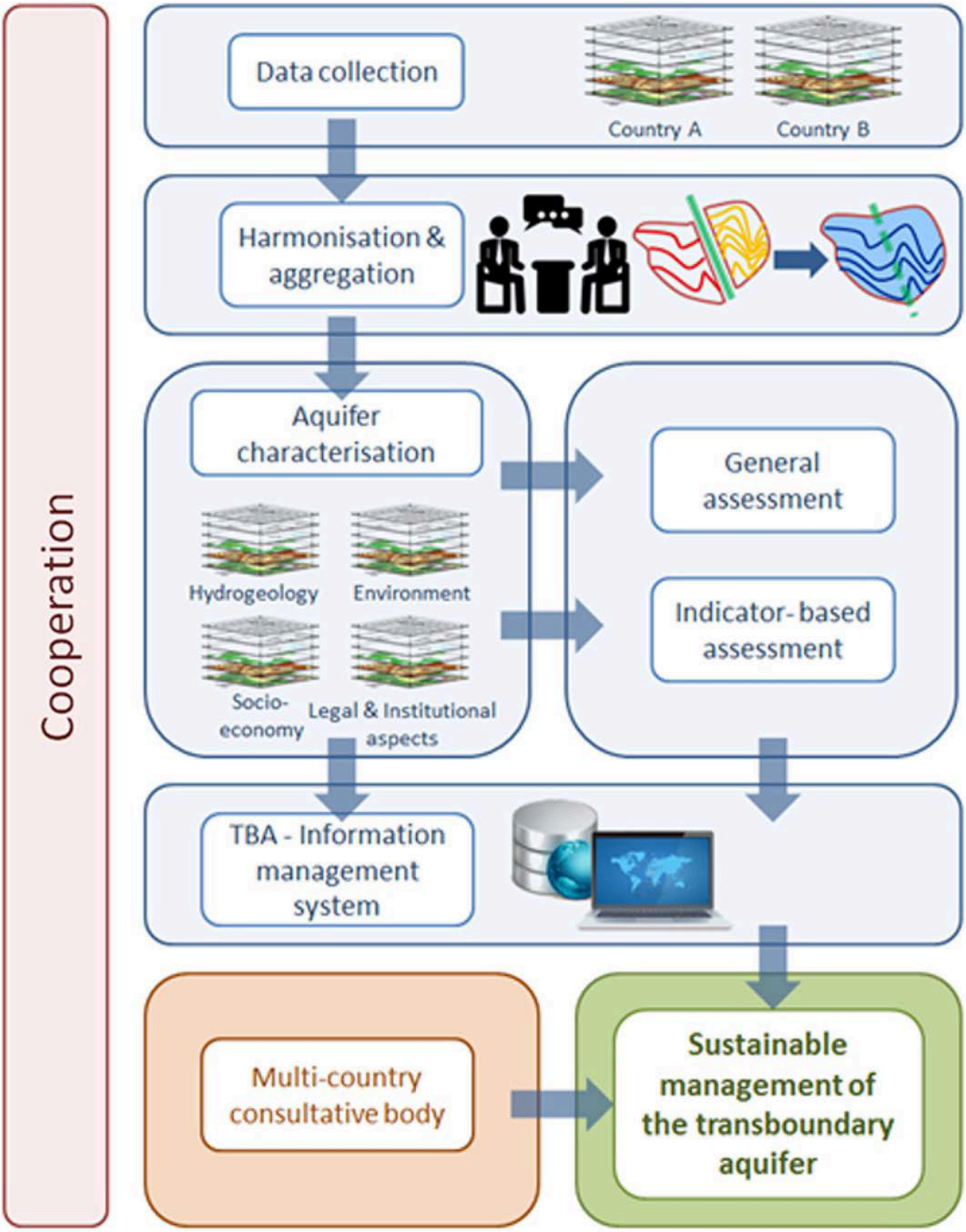


Figure 12-2 *Methodological approach adopted for the STAS assessment (Source: IGRAC & UNESCO-IHP, 2015)*

(ii) the presence of a few recharge zones which facilitate concentrated recharge during the exceptionally high rainfall events; and, (iii) via sinkholes and faults in the north-western and western boundaries of the STAS (Tredoux *et al*., 2002; Kirchner *et al*., 2002; van Wyk, 2014). Groundwater flow in the STAS is generally considered to be from north-west to south-east, and groundwater quality, in terms of Total Dissolved Solids (TDS), deteriorates in the same direction (i.e., good in the STAS north-west and poor in the STAS south-east). Although there is no mining or industrial activity in the STAS area at present, unregulated mining activities in the future might lead to pollution of the aquifer system, due to its fragility and vulnerability.

Legal and institutional components

A domestic policy, legal, and institutional framework for groundwater is in place in all the three STAS countries. The laws of the three countries regulate abstraction and potential point-source pollution through a permit system. When it comes to non-point source pollution control, other laws step in, typically environmental protection and mining Acts.

From the domestic legal and institutional perspective, it is fair to conclude that the laws in place in the STAS countries are adequate to deal with the challenges ahead for the aquifer.

Strengthening domestic capacities in the implementation and enforcement of Acts and policies is necessary to support cooperation for the management of the STAS.

There exists no legal instrument that is specific to the management of transboundary aquifers, neither at the regional (SADC) level, nor specifically regarding the STAS.

Transboundary groundwater in general is integrated into the Revised SADC Protocol on Shared Watercourses, but only to the extent that it is hydraulically linked to a surface watercourse "i.e. flowing to a common terminus" (UNESCO & IGRAC, 2016).

Groundwater is integrated in the Orange-Senqu River Commission (ORASECOM) agreement, however only indirectly.

Gender issues

Assessment of gender issues in Botswana and Namibia has shown that the current situation in terms of gender equality needs to be improved. Gender sensitivity training is rare in water-related ministries.

Women have a major responsibility for carrying water in the 90% of the households without in-house connection to water. On average, the distance travelled per day to fetch water in the STAS settlements and communal farms is 0-2 km and 6 km, respectively. This may have serious repercussions on, for example, girls' attendance at schools.

Absence of toilet facilities in 54% of the households creates special risks for women and girls in the STAS area.

Another observation was that, in agriculture, women mainly do backyard gardening while men dominate in the medium-to large scale irrigation and stock farming.

Planning and management in agriculture (as well as representation in farmer associations) are male-dominated and about 50% of women active in agriculture do not get paid for their work.

Systematic application and collection of sex-disaggregated data will facilitate a more comprehensive, quantitative gender analysis for policy making.

For more information on the scientific assessment and key findings from phase 1, the reader is referred to a technical report produced by UNESCO-IHP & IGRAC (2016).

Phase II of the GGRETA project (2016-2018) focused mainly on capacity-building modules on groundwater modeling, legal and institutional components, as well as on gender issues as they relate to groundwater management. In addition, development of the STAS numerical groundwater model was achieved through Phase II of the project. More importantly, and specific to this paper, Phase II set the baseline for establishing a cooperation mechanism for the STAS.

3.2.2. Project Ownership and Capacity Building

To ensure ownership and to fulfill an objective of building capacity, the assessment was carried out by a team familiar with the area and composed of professionals from Botswana, Namibia and South Africa. This team met regularly in the form of regional meetings that were held on a rotational basis among the three countries sharing the STAS. Such meetings also included several stakeholder consultation meetings that comprised a broader audience (e.g. governments, regional organizations, farmers, NGOs, academia, among others).

3.2.3. Baseline for the Establishment of a Cooperation Mechanism

The cooperation mechanism developed for the STAS was based on the findings of Phase I (in particular, and with reference to, the legal and institutional set up of the STAS). These make a good case to consider when setting up a groundwater governance mechanism, particularly on two points:

- First, the extraction of groundwater from the STAS, and the protection of the STAS groundwater resources from pollution, do not fall within the purview of the general norms contained in the Revised SADC Protocol on Shared water courses, and in the ORASECOM agreement. This is because the STAS and the Orange-Senqu River are not hydraulically connected and, as such, are not directly covered by the provisions of the protocol and the ORASECOM agreement.
- Secondly, institutionalizing cooperation through a MCCM will pave a way for the development of a set of STAS-specific

rules of inter-State behaviour, should the need for such rules arise. A STAS-specific agreement would crystallize such rules, eventually to allow, for example, joint investment, development, and monitoring of groundwater within the STAS by the three countries

3.2.4. Summary of Steps, Processes and Key Milestones Followed to Foster Institutionalization of Cooperation Based on Phases I and II of the GGRETA Project.

As shown in Table 12-1, the interactions of the project team (through project meetings, workshops) which consisted of multi-disciplinary experts and focal points from the three countries, the UNESCO-IHP and the high-level government representatives of the three countries presented a good platform and an opportunity for dialogue to establish what became the "STAS" family. It also became evident that the involvement of high-level decision makers and key stakeholders at an early stage, and throughout the project, facilitated buy-in, something that smoothened project execution. Led by UNESCO-IHP, a series of capacity-building modules, including modules on negotiations and conflict resolutions through the UNESCO-IHP's so-called PCCP (from Potential Conflict to Potential Cooperation) were arranged for the focal points representing the

Table 12-1 Simplified lithostratigraphy of the STAS and corresponding classification (Modified after SACS, 1980; Smith, 1984; JICA, 2002; Miller, 2008)

Geology								Hydrogeology	
Age	**Supergroup**	**Group**	**Formation/MemberSupplementary**				**Lithology**		
			Botswana (B)	Namibia (N)	S Africa (SA)	UNESCO, 2016	Simplified	STAS	
			(Smith, 1994)	(Miller, 2008)	(SACS, 1980)				
Tertiary to Quaternary	Kalahari	Kalahari				Kalahari beds	Sand, silcrete, calcrete (duricrust), gravel, sandstone, marls, clayey gravels	Unsaturated Zone	
Jurassic		Stomberg-Lava (B) Kalkrand (N) Drakensberg (SA)		Neu Loore		Kalkrand	Basalt and dolerite	Kalahari aquifers	
Triassic		Lebung (B)	Ntane			Ntane	Sandstone		
		Etjo (N)							
		Clarens (SA)	Mosolotshane						
Permian	Karoo	Ecca	Kule	Whitehill	Whitehill	Whitehill	Shale and sandstone		
			Rietmond	Rietmond	Prince Albert	Rietmond	Sandstone interbedded with shale and coral horizons	Aquitard/ aquiclude	
			Otshe	Auob		Auob	Shale, mudstone and siltstone	Auob aquifers	Stampriet Artesian Basin
			Kobe	Mukorob		Mukorob	Sandstone	Aquiratds/ aquiclude	
			Ncojane	Nossob		Nossob	Sandstone	Nossob aquifers	
Carbonif-erous		Dwyka					Glacial sediment nts	Aquitard/ aquiclude	
Cambrian	Pre-Kalahari	Nama							

interests of the threecountries, as well as other participants from a broad range of stakeholders (government, NGOs, farmers, among others). Other capacity-building initiatives, including groundwater modeling, groundwater governance, international and domestic groundwater laws, water and gender, were also undertaken. These modules targeted the STAS participating countries, as well as groundwater practitioners from other countries in Southern Africa. These platforms provided an iterative process meant to receive feedback and improve the understanding of the STAS in order to inform future management, even beyond the project life. These efforts led to the establishment of the STAS MCCM shown in Figure 12-3.

By the end of Phase I, the level of trust, openness and transparency was significantly improved, as shown by the ease (in terms of time taken and flexibility) with which important decisions were made compared to when the project started. The interactions obtained through workshops and working sessions that were undertaken on a rotational basis (from one country to the other, and also involving high-level country representatives) produced quality deliberations towards cross-border dialogue and cooperation. It was through this spirit that governance reforms were facilitated.

3.3. Description of the Multi-Country Cooperation Mechanism (MCCM)

If a resource such as water resource is shared by two or more countries, conflicts may arise due to the use and development of the resource (Uitto, 2004). To resolve these, forging cooperation arrangements between the neighbouring countries around a shared water body is critical. These arrangements are known as multi-country cooperation mechanisms (MCCM) (Uitto, 2004) and may culminate in the development of an institutional basis and legal instruments for the management and protection of the resource. These can be achieved or implemented through the use of bilateral, multi-lateral agreements, conventions and protocols pertaining to shared resources in those areas (Uitto, 2004). In the case of the STAS, the most suitable arrangement could be through the Revised SADC Protocol on Shared Water Courses of 2000 or the ORASECOM agreement. However, as already mentioned, none of these tools explicitly make provisions for groundwater governance or its protection. However, rather than establishing a new structure, the STAS countries decided to use the existing structure of ORASECOM (which is made up of the three STAS countries of Botswana, Namibia, and South Africa, as well as Lesotho, which is outside the STAS). The STAS MCCM exists for the joint governance and management of the STAS.

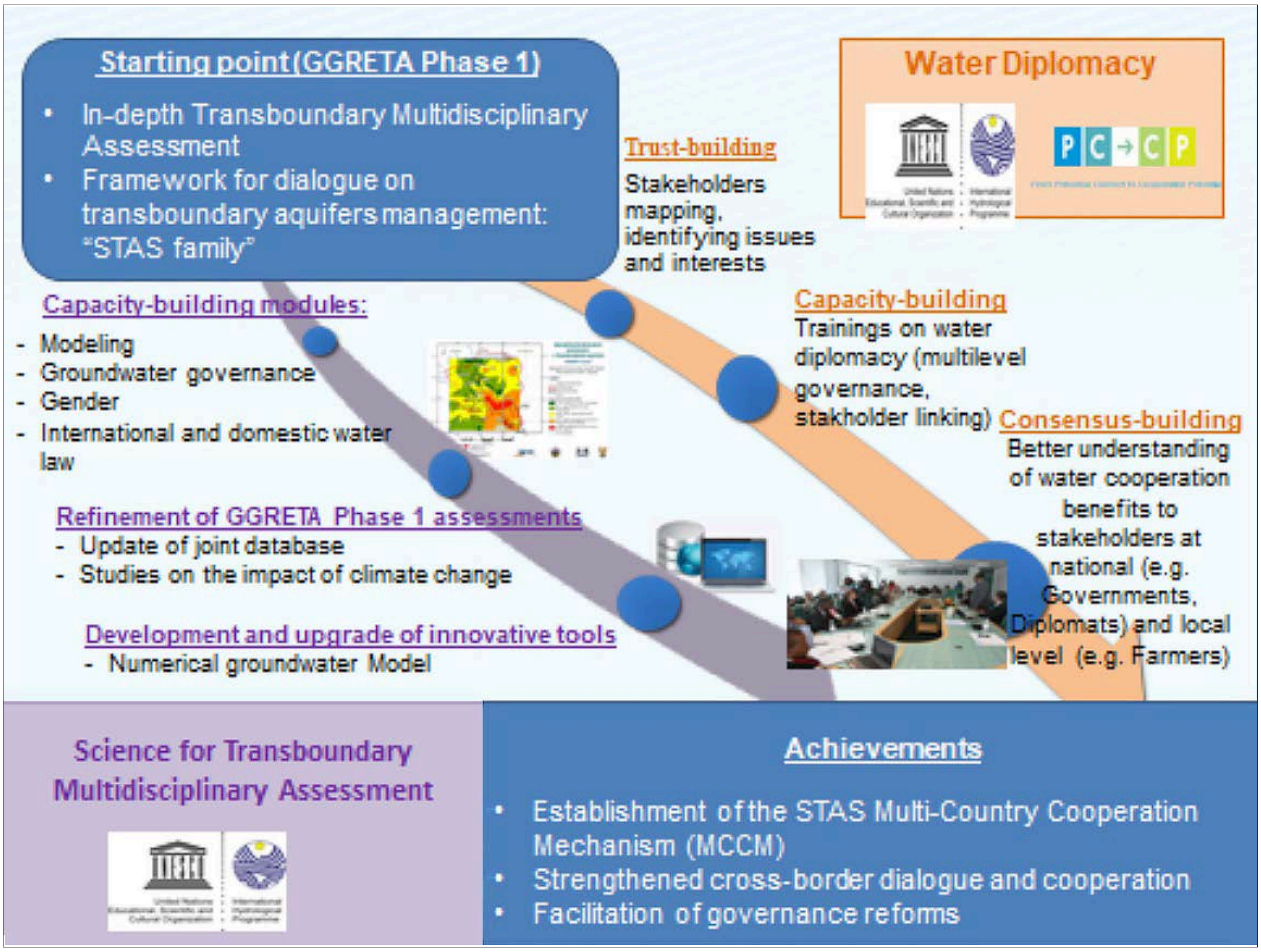


Figure 12-3 Summary of key steps and milestones leading to the establishment of the STAS MCCM (Source: UNESCO-IHP, 2016)

The steps below show a roadmap through which the STAS MCCM was established.

- In May 2017, during the 3rd Orange-Senqu River Basin Commission (ORASECOM) Ground Water Hydrology Committee Meeting (GWHC), Namibia presented a proposal to nest/institutionalise the STAS MCCM structure into the existing ORASECOM Ground Water Hydrology Committee.
- In August 2017, during the ORASECOM Council Meeting, the commissioners from the three countries supported the nesting of the STAS MCCM.
- In November 2017, during the ORASECOM Forum of the Parties, the ministers responsible for water in the three countries set milestones for the operationalization of the STAS MCCM.
- The Terms of Reference (TORs) for the operationalization of the STAS MCCM were developed and finalised between March and June 2018, with inputs from the three member states.

3.3.1. ORASECOM Structure and How the MCCM will be Incorporated.

The Orange-Senqu River Commission (ORASECOM) was formalized by the Governments of Botswana, Lesotho, Namibia and South Africa through the signing of the 'Agreement for the Establishment of the Orange-Senqu Commission' on 3rd November 2000 in Windhoek, Namibia (Earle *et al*., 2005). It is the first commission to be established following the regional ratification of the SADC Protocol on Shared Water Course Systems. ORASECOM exists to promote the equitable and sustainable development of the resources of the Orange-Senqu River, as well as providing a forum for consultation and coordination between the riparian states to promote integrated water resources management and development within the basin (http://orasecom.org/).
The structure of ORASECOM is presented in Figure 12-4. The STAS MCCM will become part of ORASECOM hosted under the Groundwater Hydrology Committee (GWHC), which falls under the Technical Task Team (TTT) structure of the ORASECOM. Through this arrangement, the STAS MCCM will enjoy the full support of ORASECOM. The MCCM will constitute the focal points (FP) from the three countries, as well as technical experts from hydrogeology, legal and institutional, and gender perspectives from the three countries. In addition, the STAS MCCM will enjoy the support of the SADC Groundwater Management Institute (GMI) which will attend as an invited member. SADC-GMI is a subsidiary structure of the SADC Secretariat established to promote sustainable groundwater management and provide solutions to groundwater challenges across the SADC region (https://sadc-gmi.org/).

Key: CTT: Communications Task Team; FTT: Financial Task

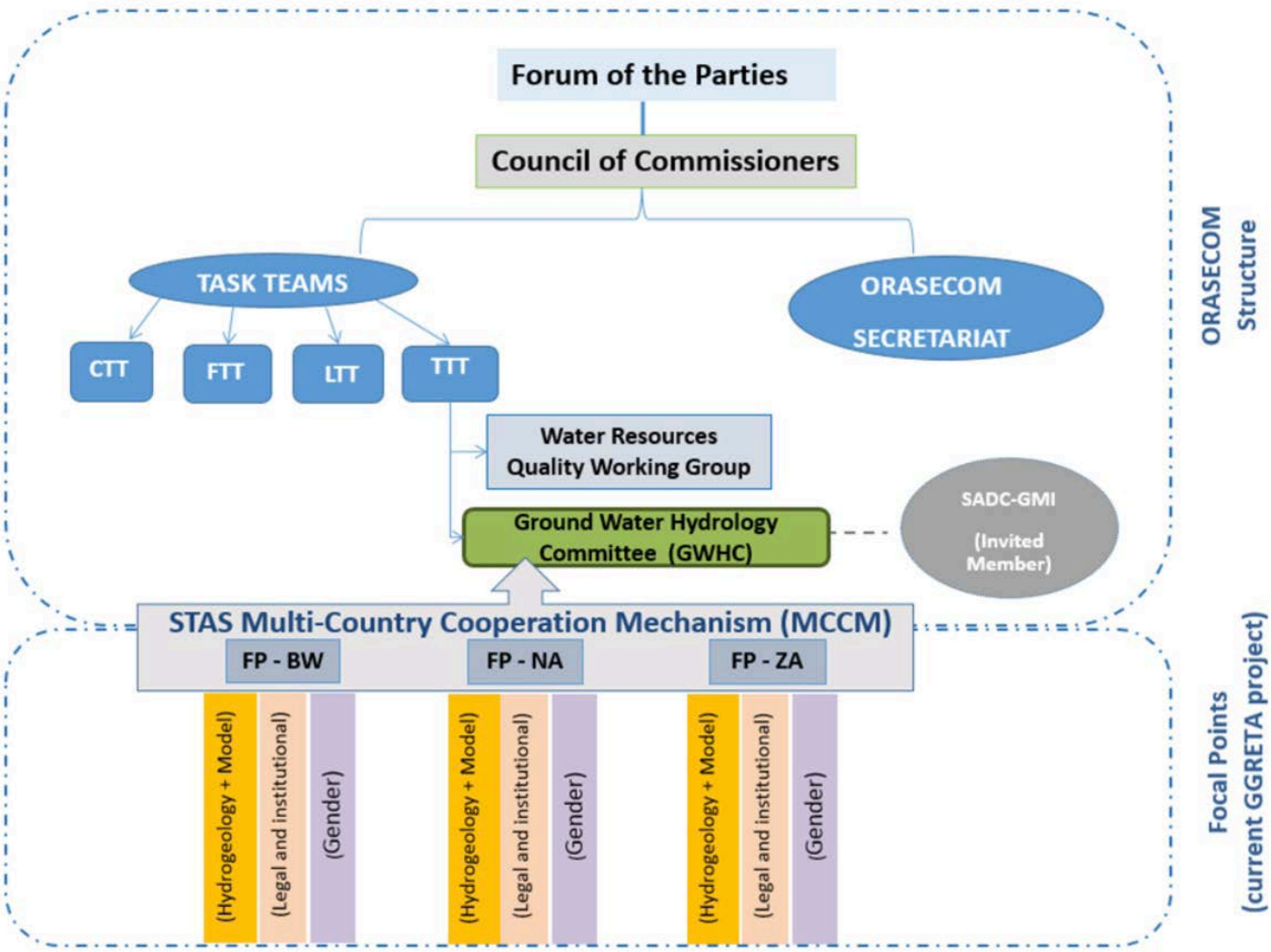


Figure 12-4 ORASECOM structure and the new STAS MCCM (ORASECOM, 2017)

Team; Legal Task Team, and TTT: Technical Task Team; FP: focal point; BW: Botswana; NA: Namibia; ZA: South Africa

3.3.2. Elements for Implementation and Improvement of the STAS MCCM

One of the cornerstones of effective governance mechanisms is the strengthening of resource monitoring and information/data collection, and data sharing protocols (Foster *et al.*, 2010). It is therefore critical that with this new mandate, ORASECOM should receive full support to enhance its capability with regards to the development of groundwater resource monitoring and data sharing protocols, improvement of its information management systems, and the development of an aquifer-wide strategic action plan that takes into account previous efforts undertaken in the basin. Previous efforts include, but are not limited to: the basin-level Orange-Senqu River basin Transboundary Diagnostic Analysis (TDA) (ORASECOM, 2013) that sought to identify and prioritise transboundary issues in the basin; the Orange-Senqu Strategic Action Programme developed in 2013 (ORASECOM, 2013), which is a basin-wide framework for the implementation of a prioritised set of national and joint transboundary actions and investments for addressing jointly agreed priority environmental concerns in the basin; and, the National Action Plans (NAPs) of the four riparian states (http://wis.orasecom.org/strategic-action-programme-for-the-orange-senqu-river-basin/). Implementation of STAS MCCM needs to build on these efforts as they provide baseline data/information that the MCCM could benefit from for effective groundwater management.

Capacity development and training on groundwater governance as it relates to current global issues, such as climate change, sustainable development goals, and public health issues (such as the COVID-19 pandemic), should receive greater attention to achieve water security in the region.

The setting up of STAS MCCM is a welcome development in the SADC region for many reasons. It is the first arrangement on transboundary aquifers since the Sustainable Development Goals (SDGs) were adopted in 2016. It is also the first operational governance mechanism to be nested in a river basin organization (i.e. ORASECOM), thus fully capturing the three pillars of integrated water resource management (IWRM) in the MCCM (such as the setting up of institutional framework, provision of an enabling environment, and management instruments required to implement the MCCM as discussed in Section 3.3.1.3). This is expected to contribute to the implementation of SDG Target 6.5 (water resources management), both at national and transboundary levels. For these reasons, the STAS acts as a pace-setter and catalyst for other TBAs to follow and consider establishing cooperation mechanisms.

3.3.3. Operationalization of the MCCM and Its Objectives

The over-arching objective of the STAS MCCM is to transition from GGRETA project-driven cooperation to permanent institutionalized cooperation among the countries sharing the STAS within the ORASECOM structure. In the short term, the STAS MCCM has already developed a tool in 2018 meant to assist with the operationalization of the MCCM. This includes establishment of an information management system (http://wis.orasecom.org/stas/). Also, a needs assessment will be undertaken to assess the current capabilities of ORASECOM pertaining to implementation of the MCCM. Development of protocols for collection and database maintenance is also a priority for ORASECOM, as well as training on operation and maintenance of ORASECOM geographic information system (GIS) viewer and data protocols. Activities of the STAS will also be reported at each meeting of the ORASECOM Groundwater Hydrology Committee (GWHC) (Section 3.3.1). The MCCM will also prioritise development of the STAS strategic action plan (SAP) based on the issues identified in Phases I and II, and generate a flow of data feeding the STAS borehole database and finalization of the STAS numerical groundwater model.

The development of a STAS numerical model went through different steps, first through the use of QGIS (an open-source GIS platform) in Phase 1 and II, which did not bear many results due to the system limitation pertaining to the complexity of the aquifer system boundaries. Currently, the model is implemented through the United States Geological Survey's (USGS) modular hydrologic model (MODFLOW 6) package (including Model muse, an interface for MODLOW and the Unsaturated Zone Flow (UZF package)) in an integrated manner to quantify groundwater flux in the STAS (UNESCO, 2020). The model will also be enhanced using remote sensing data due to observed input data limitations. Once the model has been calibrated (including steady state and transient state), it will be used to quantify the STAS groundwater resources to inform management of the STAS. It will also generate a flow of data feeding the STAS borehole database and numerical model (once operational), and report on activities at each meeting of the ORASECOM's GWHC.

In the long term, the vision is to move from data collection and exchange to joint strategizing/advising STAS countries on management of the aquifer and its resources. For example, in the current phase of the project (Phase III), ORASECOM, in partnership with UNESCO-IHP, will develop a strategic action plan (SAP), aimed at providing a framework for joint management of the STAS between the governments of Botswana, Namibia and South Africa as they address key challenges and leverage opportunities for sustainable development and use of the aquifer. Some of the current challenges in the STAS include limited groundwater level monitoring networks, particularly on the Botswana and South African sides, leading to poor long-term water level data, which affects quantification of groundwater resources. At the SADC level, there is an opportunity to either advocate for a review of the SADC Protocol on Shared water courses to explicitly consider inclusion of groundwater resources in its provisions, or develop strategies that directly promote groundwater management owing to the fact that already more than 75% of the 255 million SADC inhabitants depend on groundwater (ECA *et al.*, 2000).

04

Conclusions and Lessons Learned

Since its inception in 2013, the GGRETA project (Phases I to III) has made a significant contribution to the groundwater governance discourse, starting with a detailed multi-disciplinary scientific assessment of the STAS, leading to successful establishment and operationalisation of a STAS cooperation mechanism within ORASECOM. In many respects, particularly in southern Africa, this project may have stimulated interest in integrated transboundary groundwater assessment, as shown by a number of transboundary groundwater assessment studies in the past five years. For example, TBAs that recently underwent detailed scientific assessment include: (i) the dolomitic Ramotswa TBA shared by Botswana and South Africa (2015-2019); (ii) the Shire alluvial TBA shared by Malawi and Mozambique (2018-2019); (iii) the Tuli-Karoo Kalahari shared by Botswana, South Africa and Zimbabwe (2019-2020); and lately, (iv) the Eastern Kalahari Karoo Aquifer (EKKTBA) shared by Botswana and Zimbabwe (2020). While these TBAs are at different levels of assessments, it is highly likely that groundwater governance mechanisms will be established in these TBAs. While the shape and form of groundwater governance may differ from one TBA to the other, it is highly likely that river basin organizations (RBOs) will be used as suitable structures for groundwater management in southern Africa, drawing from the STAS MCCM model.

> *“It is recommended that more efforts be dedicated towards sharing the key lessons learned from these TBAs in order to guide future TBA studies in Africa”*

Some key lessons can be drawn from the STAS experience as follows:

- There is no one-size-fits-all solution for institutionalizing cooperation over transboundary aquifers. Each TBA is unique in terms of social, environmental, cultural, and political levels of development and scientific investigations. For these reasons, careful planning, resource mobilization and appropriate consultations are key elements worth consideration at the early stage of each TBA assessment.
- In the case of the STAS, the involvement of high-level decision makers at an early stage of, and throughout, the project proved useful in providing the requisite buy-in for key decision making, such as in deciding the model for the MCCM.
- Furthermore, a significant amount of resources should be dedicated to field work (data collection and verification of various aspects of TBAs, such as geology, hydrogeology, and environmental issues, among others).
- Trust-building among the different stakeholders, transparent negotiations and inclusiveness are also key to successful implementation of groundwater governance.
- The role of RBOs in facilitation of groundwater governance mechanisms cannot be over emphasized. Many RBOs have been successful in the development and management of river basins, mainly because they have well-resourced structures that, if used effectively, particularly for the promotion of groundwater, may deliver successful groundwater governance and cooperation mechanisms. In the case of the STAS, ORASECOM already had a groundwater hydrology committee through which the MCCM could be implemented. However, other RBOs in the region may not have these structures, and it is recommended that these RBOs be assisted to establish similar structures that will be capacitated to deal with groundwater issues.
- Capacity building and training should form a strong component of TBA assessment processes, as well as in the establishment of cooperation mechanisms. Synergies with universities and research institutions need to be strengthened to ensure sustainability, in particular on the setting up and implementation of groundwater models.
- Mainstreaming gender issues in the assessment, and monitoring and governance of groundwater is an asset, more so that gender and groundwater are intrinsically part of the SDG6. Efforts towards advancing sex-disaggregated data are essential for the management of groundwater. A methodology for sex-disaggregated data collection using multi-sectoral gender-sensitive water indicators has been developed by the UN World Water Assessment Program (WWAP) (Seager, 2015). WWAP aims at advocating for the implementation of gender-sensitive water monitoring in the post-2015 agenda, and may prove useful in TBA governance in southern Africa. For the STAS, it was observed that women have a major responsibility for carrying water in the 90% of the households with no water connection, and yet, gender sensitive training programmes are rarely considered in the STAS areas.

In view of the above, it is recommended that more efforts be dedicated towards sharing the key lessons learned from these TBAs in order to guide future TBA studies in Africa. Regional groundwater institutions, such as the SADC groundwater management institute (SADC-GMI), could play a meaningful role in this space. This may include the development of policy briefs for policy makers, as well as deliberately creating platforms for knowledge exchange and experience-sharing in its annual groundwater conferences, such as in the recent virtual SADC groundwater conference hosted by the SADC GMI in November 2020. Special sessions on knowledge-sharing and lessons learned from the Ramotswa and STAS were held during the conference.

References

Altchenko, Y., Genco, A., Pierce, K., Woolf, R., Nijsten, G., Ansems, N., Magombeyi, M., Ebrahim, G., Leutze, J., Villholth, K. G., Lefore, N., Modisha, R., Baqa, S., McGill, B. & Kenabatho, P. (2017). Resilience in the Limpopo Basin: The Potential Role of the Transboundary Ramotswa Aquifer. Hydrogeology Report IWMI, Pretoria, South Africa.

BGR, CAP-NET, WATERNET & WA-NET. (2007). Capacity Building for Groundwater Management in West and Southern Africa. Geozentrum: Hannover.

Braune, E. & Xu, Y. (2008). Groundwater Management issues in Southern Africa-An IWRM perspective. *Water SA*, 34(6), pp. 668-706.

Cuthbert, M. O., Taylor, R. G., Favreau, G., Todd, M., Shamsudduha, M., Villholth, K., Macdonald, A., Scanlon, B., Kotchoni, D., Vouillamoz, J., Lawson, F. M., Adjomayi, P., Kashaigili, J., Seddon, D., Sorensen, J., Ebrahim, G. Y., Owor, M., Nyenje, P., Nazoumou, Y. & Kukuric, N. (2019). Observed controls on resilience of groundwater to climate variability in sub-Saharan Africa. Nature, 572, pp. 230–234. https://doi.org/10.1038/s41586-019-1441-7.

Earle, A., Malzbender, D. B., Turton, A. R. & Manzungu, E. (2005). A Preliminary Basin Profile of the Orange-Senqu River, Pretoria: University of Pretoria.: A Report as part of the Inwent Capacity Development Programme: Integrated Water Resources Management in Shared River Basins in the SADC Region. https://www.academia.edu/22035140/A_Preliminary_Basin_Profile_of_the_Orange_Senqu_River). (Accessed 24/12/2020).

Ebrahim G., Father, F., Hlyatwayo, C., Keetile, K., Kenabatho, P., Leutze, J., Magombeyi, M., Majola, K., Matlhakoane, B., Modo, L., Mowaneng, P., Mugwangwavari, P., Mukuyu, P., Mutepfa, R., Netshitanini, E., Ngoni, B., Nyalungu, W., Nyikadzino, B., Petros, A., Ramusiya, F., Simba, F. & Villholth, K. (2019). Transboundary Diagnostic Analysis (Baseline Report)for the Tuli-Karoo System, International Water Management Institute (IWMI), Pretoria, South Africa. http://conjunctivecooperation.iwmi.org/wp-content/uploads/sites/38/2020/07/TuliKarooTDA-compressed.pdf. (Accessed 25/12/2020).

Economic Commission for Africa, Organisation for African Unity and African Development Bank. (2000). Safeguarding Life and Development in Africa. A Vision for Water Resources Management in the 21st Century. African Caucus Presentations – Second World Water Forum, The Hague, The Netherlands, 18 March 2000.

Foster, S. & Garduñon, H. (2013). Groundwater-resource governance: Are governments and stakeholders responding to the challenge? Hydrogeology Journal*, 21(2), pp. 317-320.*

*Foster, S., Hirata, R., Misra, S. & Garduño, H. (2010). Urban groundwa*ter use policy: Balancing the benefits and risks in developing nations, strategic overview series no. 3, GW-MATE. Washington, DC: The World Bank.

IGRAC & UNESCO-IHP. (2015a). Guidelines for Multi-Disciplinary Assessment of Transboundary Aquifers - Draft version. IGRAC Publications, Delft 2015.

______. (2015b). Transboundary aquifers of the world [map]. Scale 1: 50 000 000, edition 2015. IGRAC, Delft, Netherlands.

JICA (Japan International Cooperation Agency). (2002). The Study on the Groundwater Potential Evaluation and Management Plan in the Southeast Kalahari (Stampriet) Artesian Basin in the Republic of Namibia – Final Report.

Kirchner, J., G. Tredoux, *et al*. (2002). Applying environmental isotopes to a hydrogeological model of the Stampriet Artesian Basin Project RAF 8/029: 62 pp.

Miller, R. M. (2008). The Geology of Namibia. Windhoek, Geological Survey of Namibia.

Nijsten, G-J., Christelis, G., Villholth, K. G., Braune, E. & Gaye, C. K. (2018). Transboundary aquifers of Africa: Review of the current state of knowledge and progress towards sustainable development and management. *Journal of Hydrology: Regional Studies*, 20, pp. 21-34.

ORASECOM. (2013a). Orange–Senqu River Basin Transboundary Diagnostic Report. South Africa: http://wis.orasecom.org/transboundary-diagnostic-analysis-tda-of-the-orange-senqu-river/. (Accessed 25/12/2020).

______. (2013b). Strategic Action Programme for the Orange-Senqu River Basin. OR ASECOM Repor t 010/2014, South Africa: http://wis.orasecom.org/strategic-action-programme-for-the-orange-senqu-river-basin. (Accessed 25/12/2020).

______. (2017). ORASECOM Resolution on Nesting the Stampriet Transboundary Aquifer System (STAS) Multi-Country Cooperation Mechanism (MCCM) in ORASECOM. http://wis.orasecom.org/stas/. (Accessed 24/12/2020).

Puri, S. & Aureli, A. (2005) Transboundary Aquifers: A Global Program to Assess, Evaluate, and Develop Policy. *Groundwater*, 43(5), pp. 661-668.

SADC-GMI. (2020). Transboundary Diagnostic Analysis of the Eastern Kalahari-Karoo Basin Aquifer system. SADC-GMI report: Bloemfontein, South Africa.0 https://sadc-gmi.org/projects/water-resources-management-research-in-the-eastern-kalahari-karoo-basin-transboundary-aquifer/. (Accessed 24/12/2020).

Saunier, R. E. & Meganck, R. A. (2007). Dictionary and Introduction to Global Environmental Governance. London: Earthscan, p. 410.

Seager, J. (2015). Sex-disaggregated indicators for water assessment monitoring and reporting. Technical Paper. Gender and Water Series. WWAP. Paris, UNESCO.

Smith, R. A. (1984). The lithostratigraphy of the Karoo Supergroup in Botswana. Bulletin 26. *Geological Survey Department,* *Botswana*, 26, p. 239.

SACS (South African Committee for Stratigraphy). (1980). Stratigraphy of South Africa. Part 1 (Comp. L.E. Kent). Lithostratigraphy of the Republic of South Africa, South West Africa/ Namibia and the Republics of Bophuthatswana, Transkei and Venda. Handb. Geol. Surv. S. Afr. 8, 1–690.

Theesfeld, I. (2010) Institutional Challenges for National Groundwater Governance: Policies and Issues. *Groundwater*, 48(1), pp. 131-142.

Tredoux, G., Kirchner, J., Miller, R. M., Yamasaki, Y., Christelis, G. M. & Wierenga, A. (2002). Redefining the recharge behaviour of the Stampriet Artesian Basin, Namibia. In: Proceedings of the IAH Conference on Balancing the Groundwater Budget. 12-17 May, 2002, (Darwin, Australia).

Uitto, J. I. (2004). Multi-country cooperation around shared waters: role of monitoring and evaluation. Global *Environmental Change*, 14, pp. 5–14.

UNESCO-IHP. (2016). Governance of Groundwater Resources in Transboundary Aquifers (GGRETA)-Phase 1 – 2013-2015: Main Achievements and Key Findings, Paris, France. https://groundwaterportal.net/sites/default/files/Rapport_general_GGRETA_web.pdf. (Accessed 24/12/2020).

UNESCO-IHP & IGRAC. (2016) Stampriet Transboundary Aquifer System Assessment. Governance of Groundwater Resources in Transboundary Aquifers (GGRETA) −Phase 1: Technical Report, Paris.

van Wyk, A., Strub, H. & others. (2014). Southern African Pre-Cretaceous deep groundwater flow regimes: evidence and drivers. Golder Associates Africa (Pty) Ltd, Midrand, South Africa.

Varady, R. G., van Weert, F., Megdal, S. B., Gerlak, A., Abdalla Iskandar, C. & House-Peters, L. (2013). Thematic Paper No: 5-Groundwater Policy and Governance,: file:///C:/Users/ADMINI~1/AppData/Local/Temp/GWG_ThematicPaper5_APr2013.pdf. (Accessed 24/12/2020).

13

From Potential to Reality: Implications of Groundwater Governance for a Water-Secure Southern Africa

Tarisai Kanyepi, Vincent Itai Tanyanyiwa and Liberty Moyo

Tarisai Kanyepi, Water Policy, Pan African University of Water, Energy Sciences & Climate Change, Tlemcen, Algeria.
e-mail: tarisaikanyepi71@gmail.com
Vincent Itai Tanyanyiwa, Department Geography and Environmental Studies, Zimbabwe Open University, Harare, Zimbabwe.
e-mail: tanyanyiwavi@yahoo.com
Liberty Moyo, Dept Civil and Environmental Engineering, Namibia University of Science and Technology, Windhoek, Namibia.
e-mail: lmoyo@nust.na

Abstract

As the world grapples with climate change effects, vulnerability to water scarcity and contamination is increasing and exposing varied divisions, including classical divisions in water access, allocation and management. Globally groundwater resources play an important and increasing role in ensuring food security, or drinking water supply, and is regarded a potential buffer to drought extremity and a viable source for expansion of irrigation agriculture in Africa. However, the potential role of groundwater resources in Sub-Saharan Africa remains largely limited as it is usually overlooked and overshadowed by visible surface water sources such as lakes and rivers and/or political power dynamics that dominate water access and allocation. In Southern Africa, there's an urgent need to examine the existing groundwater governance and management systems among the various water users to ensure overall improved governance. This paper evaluates the governance of groundwater resources in Zimbabwe, Namibia and Zambia by examining their water policies in which are seeds that can be used to establish effective governance mechanisms that harness the potential of groundwater resources without threatening drinking water supply. Effective groundwater governance can be attained by harmonizing and synchronizing domestic policies with transboundary aquifer framework directives, strengthening political will, increasing knowledge and active citizenry in groundwater management. These combined efforts will go a long way toward making SDG1(no poverty), SDG2 (zero hunger), SDG6 (clean water and sanitation), SDG10 (reduced inequality) and SDG11 (sustainable cities and communities) more tangible than theoretical.

Keywords

Aquifer, groundwater management, groundwater governance, water governance, water policy

01

Introduction

1.1. Groundwater Threats and Management Gaps

Groundwater plays a pertinent and increasing role in livelihoods, food security, ecosystems, natural habitats, industries and growing cities, constituting 70% of water consumption in Europe, 70% of rural water supply in Sub-Saharan Africa, 43% global irrigation water use, 40% industrial, and 50 % municipal water withdrawals while also sustaining important ecosystem functions (IAH, 2006; UNESCO, 2012; Zektser, 2012; Zektser & Everett, 2004; Burke *et al.*, 2016; Foster *et al.*, 2015). Beyond its sectoral importance, groundwater is often the sole water source in arid and semi-arid areas and an important source of sustenance for MENA region and Sub-Saharan Africa (SSA) (Pietersen & Beekham, 2018).

> *"At a global level, groundwater issues are often overshadowed and not granted equal priority in national and international water management discourses"*

At a global level, groundwater issues are often overshadowed and not granted equal priority in national and international water management discourses. The United Nations' records, studies and normative statements express a lack of focus on groundwater. Further, the World Bank's systematic mapping of an under-researched dimension of the current global water crisis fully excluded groundwater resource data in its 2019 "Quality Unknown" Report, due to wide data gaps on groundwater (Gronwall & Danert, 2020; Rafael *et al.*, 2020). Gooijer *et al.* (2009) and Mukherji and Shah (2005) assert that despite the development of innovative approaches to ground water use in many parts of the world over the past decade, there still exists minimal attention and information on the institutional and regulative practices governing the use of these resources.

Globally, the major threats to groundwater include over abstraction, encroachment or degradation of recharge areas, deterioration in groundwater quality, and climate change (Closas, 2018). A compilation of forty modelling studies indicate projected changes in groundwater storage due to climate change will result in a general decrease in recharge in aquifers located in arid/semi-arid tropics and humid tropics (Amanambu *et al.*, 2020). However, In Southern Africa, which has over 30 shared aquifer systems, climate change, pollution, and rapidly growing water demand are rising on the agenda especially in management of transboundary aquifers in Africa. Yet, the governance of the resource is in its infancy at the national level (Mukuyu *et al.*, 2020). In African cities there is an alarming increase in informal service provision of water, (self-supply) from groundwater through hand dug wells and boreholes constituting an estimated 20 to 60% of total water supply in some cities across Sub-Saharan Africa (Foster *et al.*, 2017; Healy *et al.*, 2018; Petersen-Perlman *et al.*, 2018).

In Cape Town, South Africa, the infamous droughts of 2015-2017 prompted a "water crisis" which led to rampant groundwater abstraction due to varying demands from tourism, mining and domestic households; it is argued the situation may have been mitigated by good governance (Olivier & Xu, 2019). Nonetheless, the levels of groundwater resource development remain high in localized areas of Southern Africa and around major conurbations, with the region experiencing "economic water scarcity" owing to lack of infrastructure investment rather than " water resource scarcity" indicated by average rainfall and population density (Xu *et al.*, 2019; Mapani, 2005). Therefore, climate change will likely impact water availability, water use across transboundary basins or at local levels and all stages of the hydrological cycle, especially groundwater recharge and discharge (Varady *et al.*, 2016). Thus, global institutions outside the community of groundwater management are increasingly advocating for better management approaches in response to groundwater depletion, which they view as a geopolitical challenge to sustainable growth (Earth Security Group, 2016)

Managing groundwater has the features of "wicked or messy" problems, characterized by the contestation amongst competing interests, uses and various stakeholders with complex, changing and multifaceted systems influenced by interactive social, economic, and ecological components. These systems are subject to a range of data, information and knowledge gaps which increase uncertainties (Jakeman *et al.*, 2016). The distinction between 'groundwater governance' and 'groundwater management' remains complex since 'management' relates to the specific day-to-day actions, such as monitoring, model building, and implementation of groundwater laws to protect or use groundwater (Mukherji & Shah, 2005; Foster *et al.*, 2009). However, the differentiation is visible in practice as the scope of actors or range of activities in management are narrower than those for groundwater governance, which is argued to be more holistic and inclusive as it considers the concerns of scientists, policy makers and groundwater users (Mukherji & Shah, 2005; Villholth *et al.*, 2018).

In Africa, for example, groundwater is often excluded in water planning. Coupled with a shortage of skills to monitor compliance with standards and abstraction permits, most national policies, despite targeting sustainability, equity and efficiency in water resources, are failing to ensure effective groundwater governance (Petersen *et al.*, 2020). Southern Africa has more transboundary aquifers than transboundary river basins, with South Africa and Botswana both having the greatest number of known shared groundwater systems (Turton *et al.*, 2009). An assessment of the transboundary water policies showed that in Sub-Saharan Africa, 80% of treaties focus on surface water, 2% of treaties are groundwater oriented, and only a mere 18% of treaties are conjunctive oriented, confirming the urgent need for more effective groundwater governance systems in the region (Lautze *et al.*, 2018).

On the other hand, research findings revealed that the volume of stored underground water in Africa is twenty times more than that of surface water, and SADC Member States have 2,491 m^3/capita/year in renewable groundwater; this annual volume per capita is higher than either Europe or Asia (Upton & Danert, 2019). Only 1.5% of groundwater is utilized, which could potentially provide a critical buffer against extreme drought and short-term rainfall variability (Upton & Danert, 2019). Thus, if well managed, groundwater may provide a water source for Southern Africa with a unique potential for climate change adaptation due to groundwater's typically delayed response to climatic variability and protection from evaporation (Olivier & Xu, 2019).

FAO (2016a) asserted that the character of a country or region's groundwater governance status can only be analyzed through evaluating governance's components, namely: the actors, their roles, modes of interaction, the legal, regulatory and institutional frameworks, policies implementation, information, knowledge, and science. Thus, an adequate evaluation to verify whether effective governance exists requires evaluation of the situation beyond the national level, preferably at the sub-national, such as the provincial and district level (Foster *et al.*, 2009; Foster & Ait-Kadi, 2012). Semi-arid and arid countries are understandably more likely to overuse their water resources as postulated by climate forecasts. The lessons drawn from Southern Africa's situation can potentially indicate potential solutions or flag the dangers or irrelevance of certain standardized, or seemingly desirable, policies; policy assessment may be very relevant, especially for the whole SADC region or MENA region. Against this background, the current state of groundwater management policies and approaches of Namibia, Zambia and Zimbabwe are presented to examine the systemic and rigorous analytical critical thinking required on groundwater governance. This paper addresses the following questions:

- What are the institutional legislative frameworks and approaches and instruments used to govern groundwater monitoring, conservation and use in Zimbabwe, Zambia and Namibia?
- How have the adopted legislative and management instruments in Zambia, Namibia and Zimbabwe achieved/failed to fully achieve good governance or effective governance in groundwater resources management?
- What are the remaining gaps in groundwater regulation, monitoring and management, and how can these be redressed to improve groundwater access, conservation and management for Sub-Saharan Africa?

1.2. Evolution of Groundwater Governance

Globally, many forms of governance, each has its own literature, empirical cases,and varying levels of advancements, that have been conceptualized to understand governance. The initial understanding of the concept of governance viewed it as the exercising of political power in managing a country's affairs (Green, 2007). The contemporary understanding of governance recognizes the role of organizations, activities and interactions among a wider range of stakeholders on the principles, objectives and rules to implement and manage resources beyond state control through public participation and co-operation (Villholth *et al.*, 2017; Ross & Martinez-Santos, 2010). However, the definition of governance remains highly contested, partly due to the myriad of perspectives and disciplines from which people approach the concept. For instance, approaches may be on a basis of location and geographic levels (global governance or multi-level governance), on resources (wildlife governance or water governance), or on modes (interactive governance or adaptive governance) (Villholth *et al.*, 2017). In this paper, the definition forwarded by Foster *et al.* (2009) is adopted, which defines governance as the exercise of political, economic and administrative authority in national affairs management at all levels, with citizens articulating their interest, mediating differences and fulfilling legal rights or obligations through various mechanisms, institutions and processes at all levels (Foster *et al.*, 2009).

In freshwater governance, in the last six decades, decision-making was carried out by the central administration aimed at provision of services to the elite through engineering solutions, such as large-scale, physical infrastructure (namely dams and reservoirs), to produce new water supplies (Tuinhof *et al.*, 2011). However, owing to a growing recognition of the shortfalls of this engineering-based approach in water management, United Nation's first Water Development Report contended that the water crisis was essentially a crisis of governance due to socio-eco-political challenges crippling effective governance (Mukherj & Shah, 2005; WWAP, 2003). Thus, water governance emerged in the early 2000s largely from the development agencies and practitioners, namely Inter-American Development Bank (IADB) and the Global Water Partnership (GWP), that had been primarily concerned with water infrastructure, services and supply.

Water governance is defined as the political, social, economic and administrative systems at different levels of society that help to develop, manage and deliver water services (Rogers & Hall, 2003; 2007; Villholth *et al.*, 2017). Water governance involves a framework for effective water management characterized by socially responsible, environmentally sustainable, and economically efficient approaches. institutions and procedures that ensure accountability, stakeholder participation, and monitoring (Foster *et al.*, 2009). Water governance as a concept is also defined as a process which is context based, in which the society and economy are prodded in different modes of hierarchy that ensure an interactive nature of decision making. This decision-making may take place either through networks or through markets, depending on how the wicked water problem is framed towards common goals for the benefit of the society as a whole (Varady *et al.*, 2016). Subsequently, water governance has emerged as a tool to overcome deficiencies of technocratic and linear approaches. Those approaches negate the socio-political focus on the societal relationships and institutions (including beliefs, traditions, laws) with influence on water management (Castro, 2007; Quesada, 2011; Gupta *et al.*, 2013; Biswas & Tortajada, 2011). In practice, "demand-side" management of water is now recognized to be as critical as supply augmentation in attempting to ensure sustainability across future generations (Boxall *et al.*, 2009).

Water governance is applied at varying geographic levels, namely 'transboundary', 'regional' (e.g., the European Union) and across multiple levels (Pahl-Wostl *et al.*, 2013). Simultaneously the concept of 'effective' water governance captures the eight tenets of good governance (responsibility, accountability, transparency, efficiency, legitimacy, participation, equity and inclusiveness, and rule of law) and has led to the interchangeable use of the term 'good water governance' with 'effective water governance' in literature (ibid.) However, in practice, the ideology of good water governance has been quickly contested on the basis of a "one size fits all" connotation and exclusion of the poor. Thus, the concept of effective governance is garnering more attention and acceptability in scholarly circles, as more befitting in explaining reality as "water governance is conducted through formal and informal institutions, social relationships and more specifically through the 'rules in practice' of everyday water use'' (Franks & Cleaver, 2007).

During this same period of transitioning from a top-down, techno-physical orientation to a more bottom-up, holistic approach, the early proponents of a revisionist view - namely the International Association of Hydrogeologists (IAH) - were convinced of the distinctiveness and importance of groundwater as the major constituent of the world's freshwater. The growing abstraction of groundwater is occurring amid a global misunderstanding that underestimated and shrouded its management (Zwarteveen *et al.*, 2017; Foster & Chilton, 2003). Meanwhile, in developing countries, since 1970, "the silent revolution" of groundwater was accelerating rapidly, accounting for half of India's agricultural water use and over two-thirds in regions of China (Giordano & Villholth, 2007). The increase in over-abstraction of groundwater, failure to value the critical environmental ecological linkages, and unabated contamination presented a socio-economic tipping point which led to the introduction of the concept of groundwater governance in the late 2000s.

Thus, the concept of groundwater governance emerged as a subset of water governance, evidenced in the assessment of the various definitions brought forward to explain groundwater governance. Since its inception, a shift in the definition of the concept of groundwater governance is reflected in the elements that are explicitly incorporated, including: the definition of 'governance', 'good governance', 'environmental governance' and 'water governance' (Villholth *et al.*, 2017). Groundwater governance is defined as the 'exercise of appropriate authority and promotion of responsible collective action to ensure sustainable and efficient utilization of groundwater resources for the benefit of humankind and dependent ecosystems.'' (Foster *et al.*, 2009). Megdal *et al.* (2015) further refined and defined groundwater governance to be an overall framework consisting of laws, regulations and customs with mechanisms of engaging the various stakeholders to define how aquifers are managed and used. Three final project documents, namely the Global Diagnostic on Groundwater Governance (FAO, 2016b: 37), the Global Framework for Action to Achieve the Vision on Groundwater Governance (FAO, 2016a: 16), and the Shared Global Vision for Groundwater Governance 2030 and A Call for Action (FAO, 2016c: 5) present slightly varied definitional versions of the definition by Megdal *et al.* (2015).

In attempts to address the gap in groundwater analysis and data, several global studies and research projects (such as the Groundwater-MATE project supported by the World Bank), constitute a recognized series of reports and case study illustrations on key aspects of groundwater governance, and a wealth of information and analyses on groundwater management (Molle & Closas, 2020). Demand management instruments can also be complemented by supply-oriented policies in practice, such as recharge enhancement, conjunctive use, provisioning of alternative water sources (desalination, dew-harvesting), recharge enhancement and conjunctive use (Frija *et al.*, 2015). Nonetheless, many legal, institutional and organizational approaches have been applied, with three main types, namely, regulatory or command and control policy instruments (e.g. groundwater use rights, groundwater access, and usage codes), economic policy instruments (e.g. incentives, such as groundwater pricing, water rights transfers, pollution permits, subsidies or taxes, crop guarantee price tuning, financial sanctions) and voluntary/advisory instruments (e.g. behavioral change strategies) (Kemper, 2007; Theesfeld, 2010; Foster *et al.*, 2010). However, it is duly noted that these instruments are applied in combination, as there is no policy option which depends on one form of instrument in order to be effective. Instead, factors such as avoidance of bureaucratic inertia, conflict resolution mechanisms, and clearly defined responsibilities in implementation can ensure success (Foster *et al.*, 2010).

1.3. Principles of Effective Governance

Zwarteveen *et al.* (2017) asserts that the concept of effective governance and 'good governance' have been argued, with the latter term remaining subjective on the basis of the contextual-based nature of groundwater governance. Scholars assert that hydrogeological, institutional and socio-economic attributes have to be considered when examining the reasons for ineffective use of, and depletion of, groundwater (Chermak *et al.*, 2005; Shah, 2005; Solanes & Jouravlev, 2006; Fischhendler, 2008). There is also a growing consensus to acknowledge equity in water access, use and allocation, and stakeholders at local, national or regional levels. The adoption of Ostrom principles, such as the defining of boundaries for water resource evaluation, recognition of community rights, and stakeholder participation in groundwater management are argued to ensure good governance by some scholars (McGinnis, 2011; Ross & Martinez-Santos, 2010; Seward & Xu, 2019).

Furthermore in regards to approaches, technical regulation, economic incentives, and participatory management are argued to offer the means to address groundwater management, with their effectiveness determined by the local realities of the groundwater occurrences (hydrogeological dimensions) and the associated groundwater socio-economy. Although the principles of effective groundwater governance rely upon institutional pluralism characterized by a viable, strong and well-informed, pluralistic civil society, and government-based collaborative consultation and networking, other socio-economic dimensions (e.g. culture, values and customary traditions) may deter the attainment of effective governance if not factored in. In the realm of groundwater governance, institutional adaptation and flexibility have been gaining greater attention, in recognition that sustainable groundwater management depends on a flexible and adaptive management approach to deal with externalities, bring in technical knowledge, and ensure integration of community and instrumental groundwater governance approaches (Knüppe & Pahl-Wostl, 2011; Clifton *et al.*, 2010; Ross & Martínez-Santos, 2010; Giordano & Villhoth, 2007: 3).

Nonetheless, in practice, contemporary groundwater governance's problem lies primarily in the deficiencies inherent within the policies, leadership, awareness absence, and lack of monitoring or legal participation in relation to the groundwater sector. The role of politics to address these challenges grows as political decisions can either trigger or block effective groundwater management (Lautze *et al.*, 2019). Thus, it is noted that often no universally applicable, measurable, and normative definitions exist for the above-mentioned notions that good groundwater governance is supposed to lead. For instance, there is difficulty in applying the sustainability concept because of its multi-interpretability and close relationship with concepts like equity and fairness (UNDP, 2011).

Experience from more developed economies make it clear that improving groundwater monitoring, management, and protection requires strong stable institutions and concerted efforts at a local level (Varady *et al.*, 2016). However, experts who have studied groundwater use around the world tend to agree that too little is known about the institutions and policies that govern the use of these resources. In this case, the principle of integrity remains a pertinent and fundamental challenge in practice in the designing of institutions immune to capture by subsets of the community that self-organize to direct the institution against overall social interests. Megdal *et al.* (2015) assert that effective governance should adapt to the state of development and existing problems, which emanate from past assertion of rights and abstraction behaviour. Problems may include over abstraction or depletion, competing sectoral uses, or compromised quality; these issues need to be factored in when assessing possible governance approaches and frameworks to adopt and meet targeted policy objectives.

Also, unlike surface water, groundwater is easily appropriated simply by capturing it (the 'law of capture'), and Molle and Closas (2019) assert that state action is obviously facilitated where the legal framework allows for groundwater abstraction to be set or capped (as found in Australia, France, the Edwards aquifer, etc.), as opposed to situations where it faces legal impediments (e.g., Chile, parts of California, South Africa). Therefore, although groundwater governance is often dominated by laws and regulations issued by the government and implemented by state, it can also be community-centered (Schlager, 2007) or typified as co-management between users and the state (whereby the state recovers control of groundwater resources largely on its own initiative and regulation, although this can include a token role for user associations) (Molle & Closas, 2019). Thus, by accepting the complexity of groundwater resources management, and recognizing that the different paradigms and approaches all have a role, effective groundwater governance practices can be developed.

1.4. Analytical Framework

The study used various sources of information, namely, peer-reviewed journal articles, published reports, and databases in the public domain. Data were drawn from the global assessment of groundwater resources undertaken by GEF, GWP, IGRAC, FAO, UNDP, SADC Groundwater Management Institute (SADC-GMI), UNESCO and past scholarly papers on governance in Sub -Saharan Africa under the GWMATE and IWMI publications. The GWMATE strategic overview paper 10 by Foster *et al.* (2010) focused on groundwater governance, and provided a checklist of twenty technical, legal and institutional, policy coordination, and operational criteria for evaluating groundwater governance provision and capacity. The analysis assessed the components in groundwater governance, namely, the actors, institutional and legal framework, policies, and information and knowledge. The effectiveness of the groundwater governance at the transboundary, national and local levels was assessed using strength-weakness-opportunity-threats (SWOT) analysis, to identify the capacities, provisions, gaps in institutional and legislative frameworks, and the varied technical, managerial, regulative and economic instruments adopted in the case study countries. A benchmarking criterion from Foster *et al.* (2010), used by Pietersen and Beekham (2016) was adopted to review the technical and regulation instruments, or operational groundwater governance provisions, and institutional capacity for implementation. Foster *et al.*'s (2010) groundwater governance assessment approach provides a first assessment of the groundwater governance situation, with each of the identified gaps and institutional barriers categorized. In addition, five thematic components were used to assess the formal water policies in relation to groundwater provisions. The thematic components include conjunctive management, water pollution control, gender mainstreaming, climate change, environmental protection and institutional arrangements.

02

ZIMBABWE

2.1. Groundwater Resources in Zimbabwe

Zimbabwe is a semi-arid country with minimally low rainfall and endowed with limited water resources (Unganai, 2013). There are limited groundwater resources in comparison to surface water resources in Zimbabwe owing to the presence of massive ancient igneous rock formations where groundwater potential is comparatively low (Chikobvu, 2011). However, groundwater remains the main source of water for more than 70 percent of the population, mainly in rural areas (Unganai, 2013). In the last two decades, Zimbabwe has had sequential droughts which have increased water demand among competing water users, namely, the urban and agriculture sectors, and within the agriculture sector itself (FAO, 2013). The Precambrian crystalline rock basement which forms a continental mass outcrop is the most dominant aquifer type in Zimbabwe. This aquifer is characterized by groundwater present at shallow depths, and low yield and storage potential (Sunguro *et al.*, 2000). The deterioration and unreliability of the public water supply network systems have also led to a higher dependence on groundwater, even in urban areas.

> *"There are limited groundwater resources in comparison to surface water resources in Zimbabwe"*

- Zimbabwe has five transboundary aquifers (IGRAC, 2012):
- Limpopo Basin (Mozambique, South Africa, Zimbabwe)
- Tuli Karoo Sub-basin (Botswana, South Africa, Zimbabwe)
- Eastern Kalihari Karoo Basin (Botswana, Zimbabwe)
- Nata Karoo Sub-basin (Angola, Botswana, Namibia, Zambia, Zimbabwe)
- Medium Zambezi Aquifer (Zambia, Zimbabwe).

Another example of the potential for over-abstraction is the groundwater exploitation of the Nyamandhlovu aquifer in Zimbabwe for both Bulawayo's water supply and commercial agriculture. Detailed hydrogeological investigations since the late nineties, including recent groundwater modelling, recommend a sustainable yield for the aquifer as a whole (Beekman & Sunguro, 2015). More work, however, is needed to evaluate groundwater behavior under different abstraction and climate scenarios. Unsustainable utilization of groundwater resources may be a source of conflict between communities and countries.

2.2. Zimbabwe Water Law and Policy

Major institutional and policy reforms in Zimbabwe have always been preceded by, or occurred during, water-borne disease outbreak or drought episode and major political changes in the country. The legislative framework is formulated to address water challenges. Confronting the challenges and gaps in implementation of groundwater governance requires close attention to these legal frameworks in a given context. The legislative provisions in Zimbabwe include:

- Zimbabwe National Water Authority Act (Cap. 20:25), Regional Water Authority Act [Chapter 20:16], which stipulate the institutional frameworks guiding water and groundwater formal institutions.
- Environmental Management Act Regulations: Control of Alluvial Mining (2014), Effluents and Solid Waste Disposal (2007) (Cap. 20:27), Atmospheric Pollution Control (2009) (Cap. 20:27), and Effluents and Solid Waste Disposal (2007), the latter of which enforce effluent and solid waste management to avoid leachates seeping into groundwater.
- Public Health Act of 2002 regulates issues in line with water quality monitoring, safe water supply and household sanitation.
- Ecosystems Protection Regulations 2007 which mandate the protection of dambos (wetland) and prohibit wetland utilization.
- Sub catchment Councils Rates Regulations, 2000 then revised 2005 (Cap. 20:24), Zimbabwe National Water Authority Raw Water Tariffs Regulations, 2016 (S.I. 48) which sought to revise the water pricing structure.
- Climate change policies (2018) namely the child-friendly climate change policy, climate smart agriculture policy. A national climate policy, finalized in 2015, provides a framework to ensure a strategic approach is taken on climate adaptation, mitigation, technology, financing, public education and awareness.
- Water Policy Act (2003) stipulates that there must be 30% women and youth representation in water management institutions at sub-catchment levels.

2.3. Regulatory, Technical and Economic Instruments

An economic instrument aims to stabilize groundwater levels by reducing over abstraction, diminishing the risk of negative impacts and social conflict, delaying the need for investment in alternative water resources. They can also inspire the groundwater user to voluntarily adopt a certain behavior on the basis of price incentives; if the price is high, then consumptive use is less (Kemper, 2007). The various categories of economic instruments include direct pricing through resource abstraction fees, indirect pricing through increasing energy tariffs, the introduction of water markets, modifications to agriculture and food trade policies, and subsidies to encourage the use of more efficient irrigation technologies to achieve real water saving.

Zimbabwe's National Water Policy stipulates that an environmental impacts assessment (EIA) is required prior to undertaking activity. Irrigation development and location/siting of boreholes is allowed after a permit from the city council or rural council, depending on the region. The Government amended the Water Act to reflect a new dispensation in water use by changing what was termed 'water rights' to 'water permits', such that those who develop dams or boreholes do not have exclusive rights to use that water. Water permitting is one of the management instruments for allocating water resources to water users, as the permits allow one individual to draw water enough for their activities, leaving the rest for other water users to use (Davis & Hirji, 2014).

All boreholes and wells are mandated to be registered with Zinwa and requisite levies are paid annually to the authority and the respective sub-catchment councils. The groundwater permit is valued at $30, while permit application is valued at $60; groundwater use is tagged at $10 for domestic use and $15 for institutes. Tampering with meters attracts a meagre fine of $100. In Zimbabwe it remains mandatory for water users to install their own meters or measuring devices acceptable to ZINWA soon after entering a water abstraction agreement or obtaining a water permit from the sub-catchment council.

2.4. Institutional Framework

The key groundwater institutions in Zimbabwe are:

- Ministry of Lands, Agriculture, Water, Climate and Rural Settlement
- Environmental Management Agency, which operates at both provincial and district levels to assist in by-law formulation and ensure compliance to those laws.
- Department of Climate Change Management, which is housed in the Ministry of Environment, Water and Climate is the main entity at the forefront of formulating and leading the implementation of climate change policy in Zimbabwe
- Ministry of Transport, Communication and Infrastructural Development (MTCID), which provides technical guidance and expertise to Rural District Council's in planning and supervising rural water, sanitation and hygiene and borehole drilling, as well as pump maintenance and rehabilitation, through a small unit of the District Development Fund (DDF)
- Rural district councils, Catchment councils, sub-catchment councils, Water User Associations; the Rural District Councils Act (1996) empowers rural councils to formulate by-laws, monitor and enforce the user pays and polluter pays principle, among other aspects of natural resources management within their jurisdiction.
- Zimbabwe National Water Authority (ZINWA) is tasked with providing a framework for the development, management, utilization and conservation of the country's water resources; the Groundwater Department of ZINWA is responsible for provision of technical advice on groundwater planning, development and management to the Ministry of Environment, Climate and Water through a coordinated approach.

2.5. Managerial and Planning Instruments

Zimbabwe's catchment areas were drawn according to hydrological boundaries as the unit of basis for water planning, water-use permits issuance, establishing the rights and responsibilities of water users, and assigned responsibility for river, lake or dams monitoring and management (Davis & Hirji, 2014). The Water Act vests ownership of all water in the President rather than private land owners, with all national water policy and regulation frameworks based on the underlying concept of "integrated water resources management" (Mtisi, 2011).

2.6. Community Participation in Groundwater Management in Zimbabwe

A study conducted by Nyamwanza (2018) in Mbire District, Zambezi valley, revealed that the formal local institutions, namely ZINWA, Catchment Councils and Sub-Catchment Councils', are hardly known or their responsibilities, operations and activities acknowledged in regards to water management in the area. This suggests a gap at the grassroots level (local level) between policy and implementation in water management, despite the location of Mbire District within Manyame catchment area, and within the Lower Manyame and Angwa-Rukomechi sub-catchment areas. Priorities of ZINWA, the regulatory body responsible for provision, regulation and monitoring of groundwater, tends to be skewed more towards commercial activities than statutory functions, leaving non-experts to monitor and oversee groundwater management. This focus compromises the effectiveness of groundwater management (Makurira & Viviri, 2015). The reason for an absence of institutional activity in the area was cited to be due to the communal area's lack of sustained water use for commercial purposes, and no stake in commercial water. This observation resonated with observations from other rural communities in the country (Kujinga, 2004; Twikirize, 2005).

Although the Rural District Council oversees the spearheading of major water investments planned for the area, Chiefs, headmen, village-heads and spirit mediums are actively involved at the local level in rural communities. Chiefs are the heads in the line of traditional authority, followed by headmen, and lastly village heads. These leaders have a big influence on the utilization of rivers, streams, and boreholes in the area with respect to instituting and enforcing regulations for water use, as well as settling disputes and conflicts that may arise in the process of utilizing the resources.

All functioning boreholes in the district are run by specific committees, BWCs, which are elected annually, and chosen from among villagers who consistently use a particular borehole within a "reasonable" radius; the radius is subjectively judged by borehole users themselves. BWCs ensure the proper usage and maintenance of their particular borehole. BWCs ensure repairs are made using funds collected from users for repairs or oil for efficient borehole functioning. Furthermore, they settle disputes and conflicts that may arise among borehole users, with responsibility for borehole monitoring bestowed on every user. The traditional leaders work hand-in-glove with spirit mediums, known in the area as "homwe dzavanasekuru or masvikiro"(Gumbo & van der Zaag, 2002). Spirit mediums communicate and relay messages from the departed royal ancestors who are believed to be the real owners of the land, providers of rain and harvests or varidzi venzvimbo in the local vernacular. The departed royal ancestors are consulted in times of intense community vulnerabilities, such as droughts and floods; thus, their views on access to, and use of, commonly held natural resources as water resources are greatly respected.

2.7. Information and Knowledge

Zimbabwe: Aquifers at great depth still remain virtually unexplored, with existing data on the aquifers still scattered over many organizations. Sharing of this information is still not yet a common practice due to the costly nature of the groundwater assessment programs by mainly private mining companies, environmental agencies or ZINWA.
The hydrogeological capacity in both private and public sectors is generally weak, with need for additional hydrogeologists and training in groundwater modelling, hydrochemistry, geographic information systems (GIS), and database management to strengthen capabilities in both ZINWA headquarters and catchment management offices (Pietersen *et al.*, 2018). Many municipalities implement secondary monitoring networks of shallow monitoring wells, especially in cities dependent on groundwater for Zimbabwe, that is the city of Bulawayo. In Zambia, the city of Lusaka relies on groundwater and in Namibia, groundwater dependency is mainly in Windhoek. In Zimbabwe, there are still plans in the pipeline to provide the information online through public access platforms or a national organized database and information system.

> *"Sharing of information is still not yet a common practice due to the costly nature of the groundwater assessment programs"*

03
ZAMBIA

3.1. Groundwater Resources in Zambia

Zambia, due to its location within the Zambezi River basin and the Congo River basin, has relatively ample water supplies, primarily from a distinct rainy season, with an estimated 100 km^3 per year of surface water and an estimated 49.6 km^3 per year of annual renewable groundwater potential (DWA/JICA, 1995 as cited in Government of Zambia, 2010). Groundwater plays a significant role in Zambia's water sector by meeting 50% of the water supply requirements of the cities of Lusaka (the capital city) and Ndola. Groundwater uses are the following: 30% irrigation, 27% rural water supply, 22% livestock, and 13% urban supply (Baumle & Kang'omba, 2012). The irrigation sector's groundwater use constitutes 12% of the country's irrigated area with common traditional use of dambos (wetland) areas for small-scale groundwater irrigation commercial high-value irrigated crop production uses limestone aquifers, especially in parts of the Mpongwe Aquifer in Zambia (Foster & Ait-Kadi, 2012; Lindahl, 2014).

Groundwater is accessed from a variety of sources, namely boreholes equipped with electric pumps, hand-pumps, windmills, solar pumps, and diesel pumps. There are an estimated 11,000 boreholes (electric and hand pump) and 22,000 protected wells, based on a government inventory conducted in 1998 (GOZ National Water Policy, 2010). In Lusaka, the groundwater table is often extremely shallow due to the karst terrain, and the system of underground channels and cavities, which reduces the attenuation of pollutants through natural filtration. Groundwater gets easily polluted during the wet season in Lusaka's low-income settlements due to its many unplanned settlements where boreholes are often in very close proximity to septic tanks and pit latrines. Although groundwater is underground, it is still highly susceptible to contamination through seepage from sources above ground, such as sewage, rubbish and industrial waste (Nussbaumer *et al.*, 2016)

In Zambia, aquifers can be broadly categorized into three groups: (i) aquifers where groundwater flow is mainly in fissures, channels and discontinuities, which are subdivided into highly productive and locally productive aquifers; (ii) aquifers where intergranular groundwater flow is dominant; and, (iii) low-yielding aquifers with limited potential. Groundwater is fairly well distributed in comparison to surface water. Zambia has five trans-boundary aquifers: the Basement Aquifer; the Caprivi deep-seated aquifer; the Katangian/Lalaba Aquifer; the Arangua Alluvial aquifer;and, the Middle Zambezi aquifer.

3.2. Zambia Water Law and Policy

The legislative provisions in Zambia include:

- Water Resources Management Act (2011), replacing the repealed Water Act of 1949, to promote integrated management of both groundwater and surface water.
- Water Supply and Sanitation Sector Policy (2008)
- Constitution of Zambia (Amendment) Act (No. 2 of 2016)
- Environmental Management Act (No. 12 of 2011)
- Environmental Assessment Policy (1996)
- The Revised National Water Policy (2010)
- Statutory Instrument 18 of 2018, Charges and Fees, which stipulates revised water pricing charges for all economic uses of water
- Statutory Instrument 19 of 2018, Regulations on Licensing of Drillers and Constructors of Other Water Works Regulation
- Statutory Instrument 20 of 2018, Regulations on Groundwater and Boreholes, which tackle the issue of groundwater protection in order to improve both the quality and the distribution of the resource
- National Climate change Policy 2017, which addresses dissemination of climate change information, gender mainstreaming into all climate change adaptation and mitigation plans.

3.3. Institutional Responsibility

The key groundwater institutions in Zambia are:

- The Ministry of Development, Sanitation and Environmental Protection (MWDSEP), which is responsible for urban/rural water supply and water resources management.
- The Water Resources Management Authority (WARMA) under MWDSEP is responsible for groundwater assessment, monitoring, planning and regulation of commercial water use, and the drilling sector; it also presides over possible water conflicts or disputes.
- Department of Water Resources and Development (DWRD) under MWDSEP is responsible for water policy formulation, transboundary water issues, and the development of wellfields and dams.
- The BGR (Bundesanstalt für Geowissenschaften und Rohstoffe) is the German federal geological survey, which provides technical support to WARMA in groundwater resources management and protection measures.
- Department of Water Resources Development (to replace the Department of Water Affairs (DWA)) in the Ministry of Mines, Energy and Water Development is responsible for water resources infrastructure development for groundwater exploration, as well as International Waters.
- Water Resources Management Authority (WARMA)
- National Water Supply and Sanitation Council (NWASCO) which is a national regulator for urban and peri-urban water supply and sanitation (WSS)
- Two types of Water Supply and Sewerage service providers include Commercial Utilities (formed by joint ventures among Local Authorities) and Private Schemes (companies supplying water and sewerage services as a fringe benefit to employees).
- Residents Development Committees and Village WASHE committees (V-WASHE).

3.4. Managerial and Planning Instruments

The Water Resources Management Act of 2011 stipulates that there shall be no private ownership of water and that any permission to use water will be time-limited. Decentralization has been prioritized using the catchment as a management unit and the principle of IWRM (Integrated Water Resources Management) has been adopted in a manner which takes gender and climate change dimensions into account.

> *"Legal instruments wield tremendous influence on the nature and details of governance within a nation's boundaries and beyond"*

3.5. Regulatory and Economic Instruments

By shaping public policy, these legal instruments wield tremendous influence on the nature and details of governance within a nation's boundaries and beyond (Nanni *et al.*, 2006; Nanni & Foster, 2005; Aureli & Eckstein, 2011; McCaffrey, 2011). Constructors, drillers and engineers must be registered in a register that is maintained by the Engineering Institution of Zambia; a nominal fee of K250 ($1,377) is charged annually. Drilling and abstracting groundwater for domestic and non-commercial purposes requires a permit or authorization. A license is required to engage in the trade or business of drilling boreholes; a license is obtained through application to the Authority on payment of a prescribed fee. The Water Act stipulates regulation of groundwater de-watering by mining firms and mandates mining firm licenses for conducting dewatering; control of location/siting of boreholes ensures boreholes are not too close to sources of contamination.

An EIA is mandated to be carried out prior to an irrigation project (WARMA, 2018). A permit is needed to impound water or impede water (via weir, on-channel dam, barrage). Draining wetlands is prohibited, wetlands are restored, headwaters (i.e. river sources) are safeguarded and groundwater recharge areas are protected. Charges and fees are charged for all economic uses of water, namely hydropower, agriculture, mining, industries, municipal, as well as non-extractive uses (e.g., recreation and navigation). Exempted from charges and fees are domestic and non- commercial use of 10,000 liters/day per household. A fixed charge of K5.00 is applied for agricultural use of water of up to 100,000 liters/ day. Zambia water permits for surface water or groundwater are requisite; a one-time fee of 250 kwacha (US$25) applies to domestic boreholes and an allocation of 10,000 liters per day is given for domestic purposes above 20,000 liters per day for agricultural purposes (Tena, 2019). In addition, consumption above 10,000 liters a day attracts a fee of 5 kwacha ($0.28) per 30 cm^3 (30,000 liters) abstracted (Kaunda, 2018).

Zambia's Statutory Instruments (SIs) requires submission of applications prior to drilling and registration of all existing boreholes. Fees apply if the water will be utilised for non-domestic purposes. The SIs further prescribe specifications for a standard borehole design and distances for siting boreholes from potential sources of pollution, such as pit latrines soak-aways, garages, fuel tanks, cemeteries etc. Minimum distances are also prescribed between boreholes, considering water quantity as dictated by the hydrogeological conditions.

The Zambian government's new regulations charge commercial rates for boreholes used by more than one household. The government is promoting communities to use communal boreholes (six to nine households per borehole) rather than single household boreholes in most residential areas. The government plans to eventually decommission domestic boreholes used by single households to improve conservation of water and to raise funds (Kaunda, 2018). Installed water meter devices in Zambia measure water consumption and pollution levels in each borehole. WARMA inspectors decommission boreholes found to be leaking (Kaunda, 2018).

> *"Issues of poor financing still cripple decisive actions"*

Although rural district committees and sub-catchment councils have been adopted, issues of poor financing still cripple decisive actions by these committees. However, in Zambia the residents' Development Committees and village WASHE committees (V-WASHE) have been fully involved in groundwater projects since 2017 under the SADC-GMI and IGRAC groundwater projects. In addition, a successful approach to improve groundwater management in Zambia is the Zambia National Water Stewardship award by Water Resources Management Authority (WARMA). Since November 2018, the award promotes, incentivizes and recognizes good corporate water stewardship amongst water using companies in Zambia demonstrating sustainable water use in line with international best practice; judging criteria for the Award are based on criteria of the Africa Water Commission (AWS) Standard.

3.6. Information Management

Zambia has attained great feats in data management with the use of a borehole database, which includes geological logs encompassing a Groundwater Database and GIS mapping of groundwater resources. The first program, the Groundwater Resources Management Support Programme (GReSP), is maintained by WARMA. It was promptly followed by the GrIMS project, which collects hydrogeological and technical data for water points, namely open wells, springs and boreholes for the whole country. GrIMS is used to ensure adaptive management to climate change. The database has been linked to GIS as a visualization aid for the public and policymakers. Technical software processes data available, such as groundwater modelling or pumping test analysis. An estimated 31,000 water points have been arranged within hydrological units (basin blocks) and stored in the national database; 15,000 water points already have updated general and basic hydrological information (Tena *et al.*, 2019).

04

NAMIBIA

4.1. Namibia Groundwater Resources

Namibia is the most arid country south of the Sahara. It is classified as a water-stressed country, characterized by high inland temperatures, high evaporation rates of 3,200 mm/annum, low average humidity, and an annual average rainfall of 250 mm per annum. An exception to the water stress is found in the northern region, where the large Tsumeb–Otavi–Grootfontein carbonate groundwater aquifer is located (Mendelson *et al.*, 2002). On average, Namibia is deficient in surface water, as all but three major rivers (the Zambezi, Kunene and Kavango) are ephemeral streams.

The country relies on the following water sources: 46% is groundwater; 30% surface water (ephemeral and perennial rivers); and, 1,5% is from unconventional sources. Groundwater management is complicated by the existence of varying hydrogeological dimensions of various aquifers from different rock types, such as alluvial, fracture, karst, Kalahari, and artesian (Angula & Kaundjua, 2016). The major contamination problems in Windhoek are related to pipe- and sewer-bursts, which leak into the groundwater system. Rampant housing construction in the southern part of the capital city within the boundary of the Windhoek aquifer encroaches on the recharge zones (Mapani, 2005). Salinity, pesticides, and herbicides are huge sources of groundwater contamination in the Namibian sector of the Stampriet Artesian Aquifer where irrigated agriculture is practiced (UNESCO-IHP & IGRAC, 2016).

Namibia has eight trans-boundary aquifers:

- SE Kalahari basin/Stampriet Orange River
- Ramostwa Doloite Basin
- Euseb Graben/ Kalahari Karoo basin
- Coastal Sedimentary Basin
- Cuvela Etosha Basin
- Nata Karoo Sub-basin/Lower Caprivi
- Northern Kalahari
- South East Kalahari Karoo Basin.

4.2. Namibia Water Policy and Law

The legislative provisions in Namibia include:

- Namibian Constitution, Article 100, which states “Land, water and natural resources below and above the surface of the land….shall belong to the State….”
- Act No 54 of 1956 (Sections of South African Water Act made applicable to Namibia)
- The Namibia Water Corporation Act, Act No 12 of 1997
- The Namibia Water Resources Management Act No 24 of 2004, which was never commenced, and was subsequently revised to the Revised Namibia Water Resources Management Act, gazetted in December 2013
- Water Supply and Sanitation Policy (1993), which serves as the central policy for water and sanitation management
- National Water Policy for Namibia (2000)
- Water Supply and Sanitation Policy 2008, which applies priority rankings in case of water shortage; domestic use is the first priority, followed by economic activities to be graded on the basis of economic value
- Water Resources Management Act, 2013, which stipulates institutions to carry out groundwater monitoring and compliance checking
- Drought Policy, 2004, which makes provisions for drought management
- Environmental Assessment Policy, 1996
- Water Supply and Sanitation Policy, 2008
- Climate Change Policy, 2007

4.3. Institutional Framework

The key groundwater institutions in Namibia are:

- Namibia Water Corporation (NamWater), which is a parastatal organization responsible for bulk water supply throughout the country
- Department of Water Affairs (DWA) within the Ministry of Agriculture
- Local Authorities; urban water supply is the responsibility of the regional or city councils except for the cities of Oranjemund, Tsumeb, and Grootfontein, where water supply is developed and managed by the private sector
- Namibia Water Rural Development
- BMCs (Basin Management Committees), Water Point Committees (WPCs), and Water Users’ Associations (WUAs), for local level water management
- Private sector, providing water supply and sanitation services on private land for tourism, industry and mining
- The National Development Corporation (NDC), which works in the irrigation sector
- The Ministry of Agriculture, Water & Forestry (MAWF), which is responsible for all water sector resources management, rural water supply, and waste water
- Division of Geohydrology, which conducts groundwater investigations and groundwater management (including monitoring water quality and quantity)
- Directorate of Rural Water Supply and Sanitation, responsible for coordination of rural water use.

4.4. Regulatory and Economic Instruments

In Namibia, there are water control areas, such as the Otavi Mountain land, to curb over-abstraction of groundwater (Heyns, 2008; BIWAC, 2009). The establishment of basin management committees and a preliminary permit system have helped control abstraction of groundwater in water control areas. The permissible abstraction allocation is based on a conservative estimate of annual recharge, as well as groundwater monitoring. The Drought Policy (2010) encourages on-farm risk management for water supply, demand management and risk assessment.
In the beer brewery industry, the use of dual pipe systems allow backwash water from carbon filters to be re-used for irrigation (Government of Namibia Water Policy, 2010). In Namibia, ZESCO and the Nakambala Sugar Estates owe thousands of dollars to Water Board as irrigation water is not regarded as an economic good until shortages occur. Shortages are worsened by the provisions of Namibia's water and sanitation sector Policy (WASP) of 1993, which reduces the price of water supplied for irrigation by the state through a special subsidy (FAO, 2015).

In Namibia, permission to abstract additional water for irrigation purposes is considered if the allocated water quota for the area under consideration has not been reached. The unit quantity of irrigation water has been reduced to 10,000 m^3/ha/a (Dirkx *et al.*, 2008). Drilling of boreholes or construction of a well require a permit. A borehole license is awarded to the borehole owner as well as a license to dispose of groundwater abstracted from mining operations. The government of Namibia has control over groundwater, as the law dictates, to determine zoning of aquifer boundaries, impose or prescribe as part of license conditions requirements for enhancement of natural recharge, or to seal off any borehole situated on the land drilled without a license.

The legal framework is convoluted such that, for issues taken to court in regards to intensive over-abstraction by Valencia mine, resultant rulings have been minimally successful in context of the policies of post-independence. The development of the Windhoek Managed Aquifer Recharge Plan (2016) has led to an increase in artificial recharge. Managed Aquifer Recharge (MAR) was initially established in 2004 and by 2011, six boreholes were equipped with recharge capacity of 420 m^3/ hour. The plan's concept involves transfer of surface water to the Windhoek aquifer for safe storage and use when required. Threats posed by climate change and increasing droughts have led to the expansion of the MAR scheme, with ten new injection boreholes (with 675 m^3/hr injection capacity) and ten new abstraction boreholes (with 745 m^3/hr capacity). The city of Windhoek pays the bulk water supplier, NamWater, the operational cost of the recharge water (stored at cost price), with an additional price paid by the City if more water is withdrawn in a given year than the aquifer's natural recharge rate (1.73 mm^3/annum). The model used benefits the water users by improving water security during drought periods and provides revenue generation for NamWater (Murray, 2017).

4.5. Managerial and Planning Instruments

IWRM is stated in the policy framework of the country, however the government has is yet to revive, endorse or implement the IWRM plan of 2010 (Remmert, 2016). Decentralization has brought with it relative success in Namibia with the launch of the Community Based Management (CBM). The CBM has been launched since the 1990s for communities to manage and maintain infrastructure through collective funds raised from the community. It has immensely increased provision of clean water to many rural areas. However, cases of small villages failing to maintain water infrastructure have arisen, owing to financial management or inappropriate tariff structures. A study by Mapaure (2009) states that rural residents in three of northern Namibia's regions view the program as an imposed measure that foists the responsibility and financial burden for local water infrastructure on poor, unprepared communities and is viewed as an infringement on customary law and traditional authorities.

> *"Cases of small villages failing to maintain water infrastructure have arisen"*

4.6. Information Management

Namibia has a groundwater database, GROWAS II, which features a GIS based graphical user interface (GUI) and many query functions. It also features a modular system including time series tools, hydrochemistry, licenses for abstraction application, and groundwater status reporting functions, among others. Technical software for processing data is available, namely for groundwater modelling, pumping test analysis, hydro-chemical analysis, GIS, etc.

05

Transboundary Groundwater Resources

5.1. Shared Aquifers

The list below shows the transboundary aquifers (TBAs) shared by each of the three case study countries in this study:

- Coastal Sedimentary Basin V- Namibia South Africa
- Stampriet Aquifer System- Botswana Namibia South Africa
- Limpopo Basin- Mozambique, South Africa and Zimbabwe
- Tuli Karoo Sub-Basin- Botswana, South Africa, Zimbabwe
- Northern Kalahari/Eiseb Graben/Karoo- Angola, Botswana, Zambia and Namibia
- Save alluvial Aquifer- Mozambique, Zimbabwe
- Eastern Kalahari Karoo Basin- Botswana, Zimbabwe
- Cuvela and Ethosa Basin/Ohangwena Aquifer system- Angola, Namibia
- Nata Karoo Sub-Basin/Caprivi deep-seated aquifer- Botswana, Namibia, Zimbabwe
- Coastal Sedimentary Basin IV- Angola, Namibia
- Medium Zambezi Aquifer/ Pungwe Basin- Mozambique Zambia Zimbabwe
- Shire Valley Alluvial- Malawi Mozambique, Zimbabwe
- Arangua Alluvial- Mozambique, Zambia
- Sand and Gravel Aquifer- Malawi, Zambia- Alluvial
- Kalahai /Katangian Basin/Lualaba- DRC, Zambia
- Weathered basement- Malawi, Tanzania, Zambia

The global scale modelling (Riedel & Döll, 2015) predicts medium to high development stress under the worst-case global climate and irrigation scenarios for 2030 for the following TBAs: Karoo sedimentary aquifer; Stampriet Artesian Aquifer System; Eastern Kalahari/ Karoo Basin; Cuvelai; and, Ethosa Basin / Ohangwena Aquifer. Davies *et al.* (2013), in their analysis of transboundary aquifers, identified the Tuli Karoo Sub-Basin and the Eastern Kalahari/ Karoo Basin as the most likely to be troublesome and for which some form of international collaboration in monitoring, management and apportionment are needed now in order to avoid conflicts in the future should demographics, land use or climate, change. Currently, there are initiatives underway to better understand the Karoo sedimentary aquifer, Ohangwena Aquifer in Namibia, Stampriet Aquifer System, and Ramotswa Aquifer systems, which were revealed to have great potential for transboundary degradation of some form and require further governance intervention from member states (Herbert & Döll, 2019).

5.2. Institutional Frameworks and Managerial Instruments

The SADC-GMI was established in 2016 to enhance the institutional capacity of all SADC Member States and to promote collaborative and coordinative aspects on groundwater resources management for trans-boundary organizations. SADC-GMI has established:

- Permanent Joint Technical Commission (JPTC) between Angola and Namibia on the Kunene River
- Joint Permanent Water Commission (JPWC) between Botswana and Namibia (1990)
- Permanent Water Commission (PWC) between South Africa and Namibia on the lower Orange River
- Permanent Okavango River Basin Water Commission (OKACOM) between Angola, Botswana and Namibia
- Revised SADC Protocol on Shared Watercourses of 2000 and river basin agreements across the region.

A regional groundwater monitoring network and information system have been established, including a groundwater data portal, with compiled regional hydrogeological map and atlas for the SADC Region. The SADC GMI has successfully spearheaded the establishment of two river basin groundwater committees so far to ensure full integration of surface water and groundwater by RBO's: (i) the Limpopo Commission Groundwater Committee, in 2019, which oversees the Limpopo Basin aquifer; and, (ii) the Orange River and Sengu Commision Groundwater hydrology Committee (ORASECOM) which oversees the Ramotswa aquifer. The establishment of separate surface water and distinct groundwater committees under the River Basin Management Unit means that conjunctive management and assessments and monitoring projects can be established for transboundary aquifers.

5.2.1. Limpopo River Basin Commission

The basin is drought and flood prone with moderate to low groundwater, and low groundwater recharge rates due to low rainfall coupled with poor water-bearing capacities of the geological rocks. Thus, the basin sustains potable supplies for small gardens but not large irrigation schemes. Involvement of the community at lower levels in water management and service provision is now being considered. There is increasing community participation and consultation of NGOs by local authorities being conducted in line with IWRM principles as a response to policy directives. Nonetheless, IWRM initiatives in the Limpopo have mostly been research-oriented, with notable research projects undertaken. For example, the Challenge Program had the Wetlands project with study sites in Zimbabwe, South Africa and Mozambique (Nyagwambo *et al.*, 2008). The LIMCOM Groundwater Committee (LGC) was established as an institutional structure to drive groundwater management in the Limpopo River Basin. The LCG is chaired on a rotational basis amongst the three riparian states.
A memorandum of understanding (MOA) was duly signed between SADC-GMI and LIMCOM for collaborative efforts in

addressing groundwater issues in the basin through research pilots, workshops, and information exchange for building an integrated data management system (SADC-GMI, 2019).

5.2.2. ORASECOM (The Orange-Senqu River Commission)

ORASECOM is economically advanced as it consists of riparian states with well-advanced economies and with IWRM principles used in its planning structure (IWRM Plan 205-2024).
The flagship Lesotho Highlands Water Project (LHWP) is a series of dams constructed to divert water from Lesotho to South Africa. ORASECOM established a technical Groundwater Hydrology Committee (GWHC) in 2007. Recently, in 2017, the Stampriet Aquifer was also nested within the ORASECOM GWHC structure following the establishment of the Multi-Country Co-operation Mechanism (MCCM). The Stampriet Transboundary Aquifer System STAS joint governance mechanism captures the IWRM conjunctive management and directly contributes to Target 6.5 at national and regional levels.

5.3. Managing/Planning Instruments

Basin-wide IWRM initiatives are based on the major transboundary river basins, namely the Zambezi, Limpopo, Orange, Incomati, Okavango and the Pungwe rivers.

5.4. Information and Knowledge

Knowledge-sharing takes place during:

- SADC Water Day
- the Annual Water Research Symposium (3 groundwater conferences held to present date)
- research-related partnerships of the Water Research Fund for Southern Africa (WARFSA), WaterNet, and tertiary level training institutions

WARFSA is a regional initiative to build regional capacity in IWRM research.

5.5. Managerial and Planning Instruments

All the reforms in the region have been guided by the IWRM philosophy, as defined in the Dublin Principles and follow-up GWP publications. Countries that have gone through water sector reform in SADC include Tanzania, Zambia, Swaziland, South Africa, Mozambique, Namibia and Zimbabwe.
Localised IWRM initiatives are usually led by non-government organizations (NGOs) and are generally in response to local situations. The local initiatives however, are unique in that they tend to involve the local communities more effectively in IWRM. The GWP National Partnership in Zimbabwe developed an IWRM plan for a sub-catchment involving all stakeholders, including traditional chiefs and the local council.

5.6. Lessons and Gaps at the Transboundary Level

Although there has been advancement at the transboundary level, with results that are well designed to serve national governments, they often leave out the stakeholders within the basin, particularly local government institutions.
In most cases the stakeholders are not fully aware of their roles or operations of the river basin commissions, and there is a need to increase awareness and sensitization programs for citizens, targeting specifically local governments.
In Zimbabwe, Namibia and Zambia, the water policy framework proposes stakeholder participation at the catchment and lower-level institutions, rather than at a national level. Despite the fact that the water policy frameworks provide a crucial avenue for stakeholder participation and design a strategy for the catchment, national authorities seek to utilize stakeholder organizations at an implementation level rather than for meaningful engagement with stakeholders in policy dialogue.
There is still need for establishment of groundwater committees at a transboundary level for the remaining transboundary aquifers and also at national and local levels.

5.6.1. Lessons and Gaps in Zimbabwe

There is room for further development of groundwater resources, with only 25% of available groundwater resources being used; however, financial resources and financial allocation to (ground)water management in Zimbabwe is minimal and should be addressed through assistance of external support agencies.

In the cities of Harare and Bulawayo, there is a growing number of groundwater drilling companies and increasing waterborne disease outbreaks due to growing water stress, El-Nino induced drought effects, and incompetence of municipalities. Moreover, problems arise due to rampant construction of malls and housing on wetlands in the capital city, and illegal gold panning and mining activities along river streams due to weak enforcement measures and capacity challenges. Politics play a vested interest in the policing of the environmental measures, as there is an absence of sufficient numbers of stakeholders with more knowledge of water issues for urban areas. As a result, the parastatal ZINWA dominates water allocations and access or management discussions over the prescribed advisors. Stakeholders, such as women or youths at catchment or sub-catchment levels, are still overlooked. The CCs include representatives of districts, local representatives of various ministries, and major water users, such as commercial farmers, smallholders, and mining and urban water user representatives.
Thus, water pricing revisions and payment issues in the irrigation sector especially have stalled the efficacy of catchment and sub-catchment councils.
Chikozho (2012) asserts that there is a need to address the social, economic and political dynamics in the society. Water measures to introduce taxes on groundwater users have failed to stem the increasing domestic use of borehole water, especially in Bulawayo which struggles to provide potable water from household faucets (Banda, 2016). The water

policy fails to clearly stipulate regulatory or institutional frameworks for groundwater at local levels. However, there is little communication and coordination between the District Councils, District Development Fund, and the Catchments Councils. Lacking is a proper institutional framework through which groundwater management can be applied at the local level, since local governments are often taken as members of CCs. For instance, Bulawayo belongs to both Mzingwane and Gwayi catchment, whilst Harare is a member of the Manyame catchment (Chikozho, 2002). Therefore, there is an absence of the community members; rather, there is the institutional representation in the water institutions at meetings by individual employees of the local government, which negates the participation of public stakeholders and their views in local councils. Water users also have to travel long distances to Catchment Authority offices to pay fees and to obtain services, such as water permit renewal, as these services are solely handled by the catchment council offices (van Koppen *et al.*, 2006). As with other local governments in the region, the focus of local governments in Zimbabwe is more towards water, sanitation and hygiene (WASH) than IWRM.

5.6.2. Lessons and Gaps in Zambia

There is room for further development of groundwater resources with only a fraction of available groundwater resources currently being used. Groundwater can play a key role in clearing the backlog in access to improved drinking water supply for the rural population. However, at a local level, Nussbaumer *et al.* (2016) highlighted that Water Trusts and Local Water and Sanitation Councils lacked the capacity to fully utilize hydrogeological data for groundwater management.
Thus, training measures are needed at relevant institutions and for subordinate authorities, such as catchment and sub-catchment levels. There is a need for improved coordination among various ministries, departments and institutions dealing with water and monitoring of groundwater (Zambia National Water Policy, 2010).

5.6.3. Lessons and Gaps in Namibia

The hydrogeological capacity is reasonable; however, there is need to address groundwater institutional management at the local level in Namibia and for improved coordination and collaboration of the various water institutions, both private and public.

06

Conclusion

An overall observation is that the concept of groundwater governance and IWRM is not yet well established at a national level in relation to conjunctive management of water resources. The thinking and implementation is still very much compartmentalized, within both local governments and national institutions. Command and control instruments and relatively weak use of economic instruments is noted in the three case studies for regulating groundwater over-abstraction, especially applied at the local levels through the catchment or Sub-catchment councils. Co-management governance at a village level entails that effectiveness depends on the performance of these institutions. Many decisions and policies targeting the groundwater sector have been reformed, with the transboundary governance more advanced and adept in building strategies for groundwater resilience in comparison to the national level. Agriculture remains the biggest water user in these three case studies; however, policing and abstraction control is still minimal for the irrigation sector in all three case study countries. Implementation and enforcement are still very weak, mainly due to non-favorable political, institutional, and social contexts. The findings conclude that the remaining action for enhancing the sustainability of groundwater use in Southern Africa urgently relies on two main axes. The first is related to the improvement of the institutional (especially administration) performance of the local institutions in relation to the control and monitoring of effective groundwater law enforcement.
The second is related to the need for improved integrated governance amongst all stakeholders and a change of the currently established ethical values of various stakeholders, especially farmers and self-supply water users in cities. Ethical values supporting institutional changes, such as integrity, collaboration, accountability, trust and autonomy have to be incorporated together with technical, political, and economic issues related to the national groundwater management strategies at national levels.

“Ethical values supporting institutional changes, such as integrity, collaboration, accountability, trust and autonomy have to be incorporated together”

References

Amanambu, A. C., Obarein, O. A., Mossa, J., Li, L., Ayeni, S. S., Balogun, O., Oyebamiji, A. & Ochege, F. U. (2020). Groundwater System and Climate Change: Present Status and Future Considerations. *Journal of Hydrology,* 125163.

Angula, M. N. & Kaundjua, M. B. (2016). The Changing Climate and Human Vulnerability in North-central Namibia. Jàmbá: Journal of Disaster Risk Studies, 8(2).

Aureli, A. & Eckstein, G. (2011). Strengthening Cooperation on Transboundary Groundwater Resources. *Water International, 36*(5), pp. 549-556.

Banhire, T., Muziri, C. & Matamanda, A. R. (2019). Groundwater Management in Greater Harare, Zimbabwe. The Sustainability Ethic in the Management of the Physical, Infrastructural and Natural Resources of Zimbabwe, 283.

Bäumle, R. & Kang'omba, S. (2012). Hydrogeological map of Zambia, Lusaka Province.

Beekman, H. & Sunguro, S. (2015). Groundwater Management of the Nyamandlovu Aquifer System with special emphasis on the Nyamandlovu Wellfield: Nyamandlovu Groundwater Model–Steady State. *Harare, Zimbabwe: GIZ*.

Biswas, A. K. & Tortajada, C. (2011). Water Quality Management: An Introductory Framework. *International Journal of Water Resources Development, 27*(1), pp. 5-11.

BIWAC. (2009a). Strategic Assessment of the Uranium Province: Water Balance Study of the Swakop and Khan Rivers --- Overview of the Sampling Campaign Conducted in June/July 2009. Unpublished report by Bittner Water Consult CC issued by the Ministry of Mines and Energy / Republic of Namibia, August 2009.

Boretti, A. (2020). Implications on Food Production of the Changing Water Cycle in the Vietnamese Mekong Delta. *Global Ecology and Conservation*, e00989.

Boxall, A. B., Hardy, A., Beulke, S., Boucard, T., Burgin, L., Falloon, P. D., Haygarth, P. M., Hutchinson,T., Kovats, R. S., Leonardi, G., Levy, L. S., Nichols, G., Parsons, S. A., Potts, L., Stone, D., Topp, E., Turley, D. B., Walsh, K., Wellington, E. M. H. & Williams, R. J. (2009). Impacts of Climate Change on Indirect Human Exposure to Pathogens and Chemicals from Agriculture. *Environmental health perspectives, 117*(4), pp. 508-514.

Braune, E. & Adams, S. (2013). *Regional Diagnosis for the Sub-Saharan Africa Region*. Groundwater Governance: A Global Framework for Action, GEF.

Burke, J. (2011). Macro-economic Trends That Influence Demand for Groundwater and Related Aquifer Services. *Thematic Paper No 9*, Groundwater Governance, A Global Framework for Action. GEF, WorldBank, UNESCO-IHP, FAO and IAH. *(not a full paper, but only a summary available)*.

Burke, V., Richter, D., Greskowiak, J., Mehrtens, A., Schulz, L. & Massmann, G. (2016). Occurrence of Antibiotics in Surface and Groundwater of a Drinking Water Catchment Area in Germany. *Water Environment Research, 88*(7), pp. 652-659.

Castro, J. E. (2007). Water Governance in the Twentieth-first Century. *Ambiente & sociedade, 3*(SE), 0-0.

Chermak, J. M., Patrick, R. H. & Brookshire, D. S. (2005). Economics of transboundary aquifer management. *GroundWater*, 43(5), pp. 731–736.

Chikobvu, D. & Makarati, F. (2011). The challenges of solid waste disposal in rapidly urbanizing cities: a case of highfield suburb in Harare, Zimbabwe. *Journal of sustainable development in Africa, 13*(7), pp. 184-199.

Chikozho, C. (2002, October). Institutional development under water sector reforms: Lessons from the Mazowe catchment in Zimbabwe. In *Water demand management for sustainable development, 3rd Warsfa/WaterNet Symposium, at Dar es Salaam*.

______. (2012). Towards best-practice in transboundary water governance in Africa: exploring the policy and institutional dimensions of conflict and cooperation over water. In *Rethinking Development Challenges for Public Policy* (pp. 155-200). Palgrave Macmillan, London.

Clifton, N., Keast, R., Pickernell, D. & Senior, M. (2010). Network structure, knowledge governance, and firm performance: Evidence from innovation networks and SMEs in the UK. *Growth and Change, 41*(3), pp. 337-373.

Closas, A. & Molle, F. (2016). Groundwater governance in the Middle East and North Africa region. *International Water Management Institute: Colombo, Sri Lanka.*

Closas, A. (2018). Groundwater, the state, and the creation of irrigation communities in Llanos del Caudillo, Spain. *Water Alternatives*, 11(1).

Conti, K. I. (2017). Norms in multilevel groundwater governance and sustainable development. Unpublished Ph. D. thesis. University of Amsterdam, The Netherlands.

Davies, J., Robins, N. S., Farr, J., Sorensen, J., Beetlestone, P. & Cobbing, J. E. (2013). Identifying transboundary aquifers in need of international resource management in the Southern African Development Community region. *Hydrogeology Journal, 21*(2), pp. 321-330.

Davis, R. & Hirji, R. F. (2014). *Climate change and water resources planning, development, and management in Zimbabwe* (No. 103629, pp. 1-6). The World Bank.

Dirkx, E., Hager, C., Tadross, M., Bethune, S. & Curtis, B. (2008). Climate Change Vulnerability and Adaptation Assessment Namibia. Desert Research Foundation Namibia and Climate Systems Analysis Group. UCT, Windhoek, Namibia, pp. 149–149.

Drought Policy. (2010). Government of Namibia, accessed at https://www.lac.org.na/laws/2010/4523.pdf.

Earth Security Group. (2016). CEO Briefing: Global Depletion of Aquifers. http://programme.worldwaterweek.org/sites/default/files/esg-ceo-aquifers_0.pdf (accessed May 2020).

Famiglietti, J. S. (2014). The global groundwater crisis. *Nature Climate Change,* 4, pp. 945-948.

FAO. (2013). *GEF-FAO Groundwater Governance Project A Global Framework for Country Action Thematic Paper 5: Groundwater Policy and Governance.* Rome, Italy.

______. (2015). AQUASTAT Country Profile – Namibia. Food and Agriculture Organization of the United Nations (FAO). Rome, Italy.

______. (2016a). Global Framework for Action to achieve the vision on Groundwater Governance. UN-Food & Agricultural Organisation (for GEF, IAH, UNESCO & World Bank) Publication (Rome).

______. (2016b). Global Diagnostic on Groundwater Governance. UN-Food & Agricultural Organisation (for GEF, IAH, UNESCO & World Bank) Publication (Rome).

______. (2016c). Shared global vision for Groundwater Governance 2030 and A call-for-action. Rome, Italy. Food and Agriculture Organization of the United Nations.

FAO, UNESCO, IAH, WB & GEF. (2015). Groundwater Governance a call for action: A shared global vision for 2030. Avalilable from: http://www.groundwatergovernance.org/fileadmin/user_upload/groundwatergovernance/docs/GWG_VISION_EN.pdf.

Fischhendler, I. (2008). Ambiguity in transboundary environmental dispute resolution: The Israeli—Jordanian water agreement. *Journal of Peace Research, 45*(1), pp. 91-109.

Foster, S. S. D. & Chilton, P. J. (2003). Groundwater: the processes and global significance of aquifer degradation. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, 358(1440), pp. 1957-1972.

______. (2004). Downstream of downtown: urban wastewater as groundwater recharge. *Hydrogeology Journal*, 12, pp. 115–120.

Foster. S., Garduňo, H., Tuinhof, A. & Tovey, C. (2009). Groundwater Governance: conceptual framework for assessment of provisions and needs. GW-MATe Strategic Overview Series 1, World Bank, Washington, D. C.

______. (2010). *Groundwater Governance Conceptual Framework for assessment of provisons and needs*, pp. 1–16.

Foster, S. D., Hirata, R. & Howard, K. W. (2011). Groundwater use in developing cities: policy issues arising from current trends. *Hydrogeology Journal, 19*(2), pp. 271-274.

Foster, S. & Ait-Kadi, M. (2012). Integrated water resources management (IWRM): How does groundwater fit in?. *Hydrogeology Journal, 20*(3), pp. 415-418.

Foster, S. & Garduño, H. (2013). Groundwater-resource governance: Are governments and stakeholders responding to the challenge? *Hydrogeology Journal*, 21(2), pp. 317-320.

Foster, S. D., Hirata, R. & Andreo, B. (2013). The aquifer pollution vulnerability concept: Aid or impediment in promoting groundwater protection? *Hydrogeology Journal*, 21, pp. 1389–1392.

Foster, S., Evans, R. & Escolero, O. (2015). The groundwater management plan: in praise of a neglected 'tool of our trade'. *Hydrogeology Journal*, 23, pp. 847–850.

Foster, T., Brozović, N. & Speir, C. (2017). The buffer value of groundwater when well yield is limited. *Journal of Hydrology*. https://doi.org/10.1016/j.jhydrol.2017.02.034.

Franks, T. & Cleaver, F. (2007). Water governance and poverty: a framework for analysis. *Progress in development Studies, 7*(4), pp. 291-306. Cleaver, 2007.

Frija, A., Dhehibi, B., Chebil, A. & Villholth, K. G. (2015). Performance evaluation of groundwater management instruments: The case of irrigation sector in Tunisia. *Groundwater for Sustainable Development, 1*(1-2), pp. 23-32.

Gaffoor, Z., Pietersen, K., Jovanovic, N., Bagula, A. & Kanyerere, T. (2020). Big data analytics and its role to support groundwater management in the southern african development community. *Water (Switzerland), 12*(10). https://doi.org/10.3390/w12102796.

Giordano, M. & Villholth, K. G. (eds.). (2007). *The agricultural groundwater revolution: opportunities and threats to development* (Vol. 3). CABI.

Global Environment Facility, World Bank, UNESCO-IHP, FAO & IAH. (2016). Global Diagnostic on Groundwater Governance. Groundwater Governance, A Global Framework for Action. http://www.groundwatergovernance.org (accessed July 2020).

Gooijier, G. e., Lofgren, R., Granit, J., Jägerskog, A., Aureli, A. & Renck, A. (2009). Innovations groundwater governance in the MENA region. Stockholm.

Government of Namibia Water Policy. (2010). accessed at https://www.lac.org.na/laws/2010/4523.pdf.

Government of the Republic of Zambia. (1994). National Water Policy. Lusaka, Ministry of Energy and Water Development.

______. (2010). National Water Policy. Lusaka, Ministry of Energy and Water Development.

Green, T. R., Bates, B. C., Charles, S. P. & Fleming, P. M. (2007). Physically based simulation of potential effects of carbon dioxide–altered climates on groundwater recharge. Vadose Zone Journal, 6(3), pp. 597-609.

Grönwall, J. & Danert, K. (2020).
Regarding groundwater and drinking water access through a human rights lens: self-supply as a norm. Water, 12(2), p. 419.

Gumbo, B. & Van Der Zaag, P. (2002). Water losses and the political constraints to demand management: The case of the City of Mutare, Zimbabwe. *Physics and Chemistry of the Earth, 27*(11–22), pp. 805–813. https://doi.org/10.1016/S1474-7065(02)00069-4.

Gupta, J., Akhmouch, A., Cosgrove, W., Hurwitz, Z., Maestu, J. & Ünver, O. (2013). Policymakers' reflections on water governance issues. *Ecology and Society, 18*(1). Human Rights Lens: Self-Supply as A Norm. *Water*, 12(2), p. 419.

Healy, A., Upton, K., Bristow, G., Allan, S., Bukar, Y., Capstick, S., Danert, K., Furey, S., Goni, I., MacDonald, A., Theis, S., Tijani, M. N. & Whitmarsh, L. (2018).
Resilience in groundwater supply systems: integrating resource based approaches with agency, behaviour and choice.

Heyns, P. (2008). Application of a basin management approach to groundwater utilization in the Otavi Mountain Land, Namibia. *Physics and Chemistry of the Earth, Parts A/B/C, 33*(8-13), pp. 913-918.

Herbert, C. & Döll, P. (2019). Global assessment of current and future groundwater stress with a focus on transboundary aquifers. *Water Resources Research, 55*(6), pp. 4760-4784.

IAH. (2006). Groundwater for life and livelihoods – the framework for sustainable use.
4th World Water Forum Invitation and Briefing. International Association of Hydrogeologists, Kenilworth.

Ihemba, S. & Esterhuyse, S. (2020). Assessing the sustainability of permitted irrigation from groundwater in the Grootfontein-Tsumeb-Otavi Subterranean Water Control Area in Namibia. Groundwater for Sustainable Development, 10, 100295.

IGRAC. (2012). Transboundary aquifers of the world, 1: 50 000 000, update 2012. IGRAC, Delft.

______. (2013). Groundwater Monitoring in the SADC Region Overview. International Groundwater Resources Assessment Centre.

______. (2015). Trans-boundary Aquifers of the World. International Groundwater Resources Assessment Centre [online]: http://www.groundwaterportal.org/sites/default/files/TBAmap_2015.pdf.

IGRAC, U. I. (2015). Guidelines for Multi-Disciplinary Assessment of trans-boundary Aquifers—Draft Version. IGRAC: Delft, The Netherlands.

Jakeman, A. J., Barreteau, O., Hunt, R. J., Rinaudo, J. D. & Ross, A. (2016).
Integrated groundwater management: Concepts, approaches and challenges.
In *Integrated Groundwater Management: Concepts, Approaches and Challenges*. Springer International Publishing. https://doi.org/10.1007/978-3-319-23576-9.

Kaunda, Danstan. (2018). As wells dry, Zambia regulates use of groundwater
Source Thomson Reuters Foundation Posted 17 May 2018, published 16 May 2018,
Accessed at https://reliefweb.int/report/zambia/wells-dry-zambia-regulates-use-groundwater.

Kemper, K. E. (2007). Instruments and institutions for groundwater management.
The Agricultural Groundwater Revolution: Opportunities and Threats to Development, pp. 153–172. https://doi.org/10.1079/9781845931728.0153.

Knüppe, K. & Pahl-Wostl, C. (2011).
A framework for the analysis of governance structures applying to groundwater resources and the requirements for the sustainable management of associated ecosystem services. *Water Resources Management, 25*(13), pp. 3387-3411.

Kujinga, K. (2004). *The dynamics of stakeholder participation in water resources management in Zimbabwe: a case study of the agricultural sector* (Doctoral dissertation, University of the Western Cape).

Lautze, J., Holmatov, B., Saruchera, D. & Villholth, K. G. (2018).
Conjunctive management of surface and groundwater in transboundary watercourses: a first assessment. *Water Policy, 20*(1), pp. 1-20.

Lautze, J., Lazurko, A., Macaringue, F., Magombeyi, M., Miranda, N., Mokomela, R., Chairuca, L., Chintengo, P., Ebrahim, G., Fraser, C., Mweso, N., Nkhata, M., Phiri, P., Uka, Z., van Koppen, B., Villholth, K., Majiwa, M., Munyai, B. & Sauramba, J. (2019). Transboundary Diagnostic Analysis of Shire River-Aquifer System,
accessed at https://sadc-gmi.org/wp-content/uploads/2020/05/ENG_ShireConWat-TDA-1-3.pdf.

Lindahl, J. (2014). Environmental impacts of mining in Zambia. Towards better environmental management and sustainable exploitation of mineral resources. *Geological Survey of Sweden, 27*, p. 27.

Makurira, H. & Viriri, N. (2015). Water Permit Systems, Policy Reforms and Implications for Equity in Zimbabwe, Project Country Report, accessed at http://africa.iwmi.cgiar.org/wp-content/uploads/sites/2/2017/04/Water-Permitting-Zimbabwe-Country-Report-PI_IWMI-March-2017.pdf.

Mapani, B. S. (2005). Groundwater and urbanisation, risks and mitigation:
The case for the city of Windhoek, Namibia. *Physics and Chemistry of the Earth, 30*(11-16 SPEC. ISS.), pp. 706–711. https://doi.org/10.1016/j.pce.2005.08.011.

Mapaure, C. (2009). *" Water Wars": Legal Pluralism and Hydropolitics in Namibian Water Law* (Doctoral dissertation, University of Namibia).

McGinnis, M. D. (2011). An Introduction to IAD and the Language of the Ostrom Workshop:
A Simple Guide to a Complex Framework. *Policy Studies Journal, 39*(1), pp. 169–183. https://doi.org/10.1111/j.1541-0072.2010.00401.x.

Mechlem, K. (2016). Groundwater governance:
The role of legal frameworks at the local and national level—Established practice and emerging trends. *Water*, 8(8), p. 347.

Mendelson, J., Jarvis, A., Roberts, C. & Robertson, T. (2002). Atlas Of Namibia. *A Portrait of the Land and*.

Megdal, S. B., Gerlak, A.K., Varady, R.G. & Huang, L-Y. (2015). Groundwater governance in the United States: Common priorities and challenges. *Groundwater*, 53(5), pp. 677-684.

Molle, F. & Closas, A. (2019). Groundwater governance. *Encyclopedia of Water: Science, Technology, and Society*, 1-9.

______. (2020). Why is state-centered groundwater governance largely ineffective? A review. *WIREs Water*, 7(1). https://doi.org/10.1002/wat2.1395.

Mtisi, S. (2011). Water reforms during the crisis and beyond: understanding policy and political challenges of reforming the water sector in Zimbabwe. *ODI Working Paper*, (333).

Mukuyu, P., Lautze, J., Rieu-Clarke, A., Saruchera, D. & McCartney, M. (2020). The devil's in the details: data exchange in transboundary waters. *Water International*, 1–17. https://doi.org/10.1080/02508060.2020.1850026.

Mulenga, M. & McGranahan, G. (2011). Groundwater Self-Supply in Peri-Urban Settlements in Zambia. In 6th Rural Water Supply Network Forum.

Müller Schmied, H., Adam, L., Eisner, S., Fink, G., Flörke, M., Kim, H., Oki, T., Portmann, F. T., Reinecke, R., Riedel, C., Song, Q., Zhang, J. & Döll, P. (2016). Impact of climate forcing uncertainty and human water use on global and continental water balance components. *Proceedings of the International Association of Hydrological Sciences, 374*, pp. 53-62.

Mukherji, A. & Shah, T. (2005). Groundwater socio-ecology and governance: a review of institutions and policies in selected countries. *Hydrogeology Journal*, 13(1), pp. 328-345.

Murray, N. (2017). Urban disaster risk governance: A systematic review.

Nanni, M. & Foster, S. (2005). Groundwater resources: shaping legislation in harmony with real issues and sound concepts. *Water policy*, 7(5), pp. 543-550.

Nanni, M., Burchi, S., Mechlem, K. & Stephan, R. M. (2006). Legal and institutional considerations. *Non-renewable Groundwater Resources: A Guidebook on Socially Sustainable Management for Water-Policy Makers Paris: United Nations Educational, Scientific and Cultural Organization (IHP-VI series on groundwater 10)*, pp. 49-57.

Nussbaumer, D., Sutton, I. & Parker, A. (2016). Groundwater data management by water service providers in peri-urban areas of Lusaka. *Water (Switzerland), 8*(4), pp. 1–12. https://doi.org/10.3390/w8040135.

Nyagwambo, N., Chonguiça, E., Cox, D. & Monggae, F. (2008). *Local Governments and IWRM in the SADC Region. March*, 58. www.iwsd.co.zw.

Nyamwanza, A. M. (2018). Local institutional adaptation for sustainable water management under increasing climatic variability and change. *International Journal of Climate Change Strategies and Management*.

Olivier, D. W. & Xu, Y. (2019). Making effective use of groundwater to avoid another water supply crisis in Cape Town, South Africa. *Hydrogeology Journal, 27*(3), pp. 823-826.

Pahl-Wostl, C., Arthington, A., Bogardi, J., Bunn, S. E., Hoff, H., Lebel, L., Nikitina, E., Palmer, M., Poff, L. N., Richards, K., Schlüter, M., Schulze, R., St-Hilaire, A., Tharme, R., Tockner, K. & Tsegai, D. (2013). Environmental flows and water governance: managing sustainable water uses. *Current Opinion in Environmental Sustainability, 5*(3-4), pp. 341-351.

Pavelic, P., Villholth, K. G., Shu, Y., Rebelo, L. M. & Smakhtin, V. (2013). Smallholder groundwater irrigation in Sub-Saharan Africa: country-level estimates of development potential. *Water International*, 38(4), pp. 392-407.

Petersen-Perlman, J. D., Megdal, S. B., Gerlak, A. K., Wireman, M., Zuniga-Teran, A. A. & Varady, R. G. (2018). Critical issues affecting groundwater quality governance and management in the United States. *Water (Switzerland), 10*(6). https://doi.org/10.3390/w10060735.

Petersen, C., Turco, M. J., Vinson, A., Turco, J. A., Petrov, A. & Evans, M. (2020). Groundwater Regulation and the Development of Alternative Source Waters to Prevent Subsidence Houston Region, Texas, USA. *Proceedings of the International Association of Hydrological Sciences, 382*, pp. 797–801. https://doi.org/10.5194/piahs-382-797-2020.

Pietersen, K. & Beekman, H. (2018). Groundwater Management in the Southern African Development Community., accessed at https://www.researchgate.net/profile/Kevin_Pietersen/publication/309806837_Groundwater_management_in_the_Southern_African_Development_Community/links/5824322608aeb45b58898c85/Groundwater-management-in-the-Southern-African-Development-Community.pdf.

Quesada, M. G. (2011). Water and sanitation services in Europe: do legal frameworks provide for "good governance"?.

Rafael, S. C., Jan, F. W., Jenny, G., Johannes, van dder K. & Kerstin, D. (2020). pte d M us pt. *Environmental Research*, 0–31. https://doi.org/10.1088/1748-9326.

Remmert, D. (2016). Water governance in Namibia: a tale of delayed implementation, policy shortfalls, and miscommunication. *Democracy Report, 13*, pp. 1-20.

Riedel, C. & Döll, P. (2015). Global-scale modeling and quantification of indicators for assessing transboundary aquifers GEF Transboundary Waters Assessment Programme (TWAP), Frankfurt.

Rogers, P. & Hall, A. W. (2013). Effective Water Governance Background.

Ross, A. & Martinez-Santos, P. (2010). The challenge of groundwater governance: Case studies from Spain and Australia. *Regional Environmental Change, 10*(4), pp. 299–310. https://doi.org/10.1007/s10113-009-0086-8.

SADC. (2009). Regional awareness and communication strategy for the SADC water sector available at http://www.sadc.int/files/2213/5293/3542/SADC_CommunicationStrategyforWaterSector2008pdf (accessed June 2020).

______. (2011). Regional Agricultural Policy- Country Summary Agricultural Policy Review Reports. available at http://www.sadc.int/fanr/docs/rap/RAP Combined Summary Reports- 8 May 2011.pdf (accessed July 2020).

______. (2014). Director of the SADC-Groundwater Management Institute [Online]. Gaborone, Botswana: Southern Development Community. available at: http://www.sadc.int/opportunities/employment/employment-archive/director-sadc-groundwatermanagement-institute/ (accessed 2 July 2020).

SADC-GMI (Southern African Development Community Groundwater Management Institute). (2019). Groundwater Report 2019, accessed at https://sadc-gmi.org/publications/.

Schlager, E. (2007). Community management of groundwater. *The agricultural groundwater revolution: Opportunities and threats to development, 3*, pp. 131-152.

Schmeier, S. (2010). International Conference “Transboundary Aquifers: Challenges and New Directions” (ISARM2010). Effective Governance of Transboundary Aquifers Through Institutions – Lessons Learned from River Basin Organizations, available at SSRN: https://ssrn.com/abstract=1747712 or http://dx.doi.org/10.2139/ssrn.1747712.

Seward, P. & Xu, Y. (2019). The case for making more use of the Ostrom design principles in groundwater governance research: a South African perspective. *Hydrogeology Journal*. https://doi.org/10.1007/s10040-018-1899-7.

Shah, T. (2005). Groundwater and human development: challenges and opportunities in livelihoods and environment. *Water Policy, 51(8)*, pp. 27–37.

Solanes, M. & Jouraviev, A. (2006). *Water Governance for Development and Sustainability, CEPAL-SERIE RecursosNaturals e Infraestrutura No. 111*. Santiago, Chile: United Nations Publication.

Sunguro, S., Beekman, H. E. & Erbel, K. (2000). “Groundwater regulations and guidelines : crucial components of integrated catchment management in Zimbabwe”. *1st WARFSA/WaterNet Symposium: Sustainable Use of Water Resources; Maputo, 1-2 November 2000, November*, 1–7. http://www.waternetonline.ihe.nl/downloads/uploads/symposium/mozambique-2000/SUNGURO.PDF%0A http://www.bscw.ihe.nl/pub/bscw.cgi/S4cba3cbd/d2607933/SUNGURO.PDF.

Tena, T. M., Mwaanga, P. & Nguvulu, A. (2019). Hydrological Modelling and water resources assessment of Chongwe River catchment using WEAP model. *Water, 11*(4), p. 839.

Theesfeld, I. (2008). A review on national groundwater policy instruments–Grasping institutional aspects for transboundary groundwater governance. In Proceedings of the 12th annual International Association for the Study of the Commons (IASC) Conference. Cheltenham, England. accessed at http://iasc2008.glos.ac.uk/conference%20papers/papers/T/Theesfeld_155301.pdf.

______. (2010). Institutional challenges for national groundwater governance: Policies and issues. *Ground Water*, 48, pp. 131-142.

Tuinhof, A., Foster, S., van Steenbergen, F., Talbi, A. & Wishart, M. (2011). Appropriate groundwater management policy for Sub-Saharan Africa.

Turton, B. A., Patrick, M., Cobbing, J. & Julien, F. (2009). The Challenges of Groundwater in Southern Africa. *Environmental Change and Security Program Report 13, 2*, pp. 71–75.

Twikirize, D. (2005). *An assessment of traditional water management practices and their implications for improved water governance in the Limpopo Basin: case of the Sibasa Dam in Mzingwane Catchment Zimbabwe* (Doctoral dissertation, University of Zimbabwe).

UNDP. (2011). Statistics of the Human Development Report (UNDP) Human Development Report Office, New York, 2011). http://hdr.undp.org/en/statistics/.

______. (2012). *Africa Human Development Report 2012 Towards a Food Secure Future* (No. 267636). United Nations Development Programme (UNDP).

UNESCO-IHP & IGRAC. (2016). Stampriet Transboundary Aquifer System Assessment. Governance of Groundwater Resources in Transboundary Aquifers (GGRETA) − phase 1. Paris.

Unganai, L. S., Troni, J., Manatsa, D. & Mukarakate, D. (2013). Tailoring seasonal climate forecasts for climate risk management in rainfed farming systems of southeast Zimbabwe. *Climate and Development,* 5(2), pp. 139-152.

UNESCO. (2012). Groundwater and global change: trends, opportunities and challenges. United Nations World Water Assessment Programme. UNESCO, Paris.

Upton, K. & Danert, K. (2019). Groundwater’s contribution to water security in Africa. http://nora.nerc ac.uk/id/eprint/524431/1/ Groundwater%20Water%20Security%20Africa%%20-%20AWW2019.pdf (assessed 8 March 2020).

UN-Water. (2013). Water security and the global water agenda—A UN-Water analytical brief. Hamilton: United Nations University. ISBN: 9789280860382.

Van Koppen, B., Moriarty, P. & Boelee, E. (2006). *Multiple-use water services to advance the millennium development goals* (Vol. 98). IWMI.

Varady, R. G., Zuniga-Teran, A. A., Gerlak, A. K. & Megdal, S. B. (2016).

Modes and approaches of groundwater governance: A survey of lessons learned from selected cases across the globe. *Water (Switzerland)*, 8(10), pp. 1–24. https://doi.org/10.3390/w8100417.

Villholth, K. G., Lopez-Gunn, E., Conti, K., Garrido, A. & Van Der Gun, J. (eds.). (2017). Advances in groundwater governance. CRC Press.

Villholth, K. G. & Conti, K. (2018). Groundwater governance: Rationale, definition, current state and heuristic framework. Advances in groundwater governance, 3-32.

WARMA. (2018). *Water Resources Management and Regulations Introduction to Statutory Instruments*. http://www.warma.org.zm/.

WWAP, U. (2003). United Nations world water assessment programme. The world water development report 1: Water for people, water for life.

Xu, Y. S., Yan, X. X., Shen, S. L. & Zhou, A. N. (2019). Experimental Investigation on the Blocking of Groundwater Seepage from a Waterproof Curtain During Pumped Dewatering in an Excavation. *Hydrogeology Journal, 27*(7), pp. 2659-2672.

Zambia Water Policy. (2010). accessed at https://www.mwdsep.gov.zm/?page_id=5164.

Zekster, I. S. & Everett, L. G. (2004). Groundwater Resources of the World and Their Uses: Series on Groundwater.

Zektser, I. S., Everett, L. G. & Dzhamalov, R. G. (2006). *Submarine Groundwater.* CRC Press.

Zektser, I. S., Potapova, E. Y., Chetverikova, A. V. & Shtengelov, R. S. (2012). Perspectives of Artificial Recharge of Groundwater in Southern European Russia. Water Resources, 39(6), pp. 672-684.

Zektser, I. S. (2012). Investigation of transboundary aquifers in Russia: Modern State and Main Tasks. In *Transboundary Aquifers in the Eastern Borders of The European Union* (pp. 79-85). Springer, Dordrecht.

Zimbabwe. (2000). Statutory Instrument 33, Water (Catchment Councils) Regulations of Regulations of 2000. Government Printers. Harare.

______. (2011). Statutory Instrument 21 No. 5. Water (Subcatchment Council Rates) (Amendments) Regulations, Government Printers.

ZINWA (Zimbabwe National Water Authority). (2007). Assessment of Surface Water Resources of Zimbabwe and Guidelines for Planning. Harare, Zimbabwe.

______. (2014). Annual Report 2014.

Zwarteveen, M., Kemerink-Seyoum, J. S., Kooy, M., Evers, J., Guerrero, T. A., Batubara, B., Biza, A., Boakye-Ansah, A., Faber, S., Flamini, A. C., Cuadrado-Quesada, G., Fantini, E., Gupta, J., Hasan, S., Horst, R., Jamali, H., Jaspers, F., Obani, P., Schwartz, K,, Shubber, Z., Smit, H., Torio, P., Tutusaus, M. & Wesselink, A. (2017). Engaging with the Politics of Water Governance. *Wiley Interdisciplinary Reviews: Water, 4*(6), e1245.

Index

Subject Index

Location Index

Groundwater supplies nearly half of all drinking water globally and is a key resource for basic livelihood from irrigated agricultural purposes to industrial purposes. It highly influences to ecosystems by maintaining the baseflow of rivers, preventing seawater intrusion, and many other benefits, which will be affected by the impacts of climate change. Despite the critical role of groundwater, often it is less considered in decision-making processes due to lack of awareness.

There are approximately 300 transboundary aquifers, supporting many of the 2 billion people who depend on groundwater according to UN-Water. Mismanagement of transboundary groundwater can cause potential national and international conflicts. Cooperation is essential and appropriate groundwater resources management based on proper legal and institutional frameworks is primarily required for achieving the 2030 Agenda for Sustainable Development as it highlights peace and prosperity for people.

This GWSI Series, the role of sound groundwater resources management and governance to achieve water security, aims to highlight the critical role groundwater to achieve water security. The beneficial use of groundwater should receive more attention since it plays a critical role in water resources management. This series explores various case studies, literature reviews, tools, and protocols for groundwater resources management and governance.

unesco
Intergovernmental Hydrological Programme

9 789231 004681

i-WSSM
International Centre for Water Security and Sustainable Management under the auspices of UNESCO