SOURCE WATER PROTECTION AND DIVERSIFICATION FOR RESILIENT URBAN WATER SUPPLY

Desk review on the enabling factors for resilient urban water supply using source water protection and diversification

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ACRONYMS

AAWSA	Addis Ababa Water and Sewerage Authority
ADF	African Development Fund
AfDB	African Development Bank
AGWA	Automated Geospatial Watershed Assessment
AMTC	Annual Million Tree Challenge
ANA	*Agência Nacional de Águas e Saneamento Básico*
AwBA	Awash Basin Authority
BGR	Federal Institute for Geosciences and Natural Resources
cm	Centimeters
C	Celsius
CaBA	Catchment-based Approach
COP27	Sharm el-Sheikh Climate Change Conference
CRIDA	Climate Risk-based Decision Analysis
CWA	City Water Authority
DAPP	Dynamic Adaptive Policy Pathways
DEM	Digital Elevation Model
DMQ	Metropolitan District of Quito (*Distrito Metropolitano de Quito*)
EPMAPS	*Empresa Pública Metropolitana de Agua Potable y Saneamiento de Quito*
FEHIDRO	State Water Resources Fund
FAO	Food and Agriculture Organization of the United Nations
FONAG	Environmental Fund for the Protection of Basins and Water
FREEWAT	Free and Open-Source Software Tools for Water Resource Management
GMP	Groundwater Management Plan
GIS	Geographic Information System
GLAAS	Global Analysis and Assessment of Sanitation and Drinking Water
Ha	Hectares
HEC	Hydrologic Engineering Center
ICM	Integrated Catchment Management
IDB	Inter-American Development Bank
ISARM	Internationally Shared Aquifer Resources Management
IWRM	Integrated Water Resources Management
km	Kilometers
km^2	Square Kilometers
KII	Key Informant Interview
LGU	Local Government Unit
LMIC	Low- and Middle-Income Country
LuWSI	Lusaka Water Security Initiative
LWSC	Lusaka Water Supply and Sanitation Company
m^3	Cubic Meters

mm	Millimeters
M	Million
MCM	Million Cubic Meters
MLD	Million Liters per Day
ModTPs	Modular Treatment Plant
MTFI	Million Trees Foundation Inc.
MWI	Ministry of Water and Irrigation
MWSS	Metropolitan Waterworks and Sewerage System
NBS	Nature-Based Solutions
NEDA	National Economic and Development Authority (the Philippines)
NGO	Nongovernmental Organization
NRW	Non-Revenue Water
NWRB	National Water Resources Board
ODA	Official Development Assistance
PCJ	Piracicaba, Capivari, and Jundiaí
PES	Payment for Ecosystem Services
PPP	Public-Private Partnership
RBO	River Basin Organization
RDS	Robust Decision Support
RQ	Research Question
SEI	Stockholm Environment Institute
SWAT	Soil and Water Assessment Tool
SWP	Source Water Protection
TNC	The Nature Conservancy
URBAN WASH	Urban Resilience by Building and Applying New Evidence in WASH
UN	United Nations
USAID	United States Agency for International Development
WASH	Water, Sanitation, and Hygiene
WCWSS	Western Cape Water Supply System
WHO	World Health Organization
WMI	Water Management Initiative
WRM	Water Resources Management
WSP	Water Safety Plan
WTP	Water Treatment Plant

GLOSSARY OF TERMS

Term	Definition
Aquifer	A body of porous rock or sediment saturated with groundwater.
Biophysical risks	A spectrum of environmental risks caused by the interaction between humans, other biological organisms, and the geophysical environment. Examples of these risks include temperature shifts, flooding, and drought.
City water authority (CWA)	An official body responsible for providing water to a city. These are often water utilities, but can be river basin authorities, as well as national water agencies.
Climate change	A change of climate, attributed directly or indirectly to human activity, that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods.
Desalination	The process of removing salt from seawater.
Diversification	A set of actions taken to achieve a portfolio of water sources and strategies that reduce short- and long-term risks to urban water supply.
Finance challenges	In the area of water management, it is a spectrum of challenges that impede sustainable and adaptable long-term financing for water-related projects and actions. Examples of these challenges include lack of funding and inadequate cost recovery for provided water.
Gender equality	A state in which both men and women have equal opportunity to benefit from and contribute to economic, social, cultural, and political development; enjoy socially valued resources and rewards; and realize their human rights.
Governance challenges	A spectrum of challenges that stem from the political, social, economic, and administrative systems that influence decision processes. Examples of these challenges around water include conflicting policies, transboundary conflict, intersectoral conflict, and power imbalances.
Gray literature	Materials and research produced by organizations outside of the traditional commercial or academic publishing spheres. Examples include reports, official documents, or working papers.
Groundwater	Water in saturated zones beneath the land surface.
Peer-reviewed literature	Work often published in scholarly journals that has undergone a peer review process or has been evaluated by outside experts.
Planning capacity	In the area of water management, the ability of CWAs to access information and tools, and the capacity to use them to carry out robust water planning.
Public-private partnerships (PPPs)	Long-term arrangements between public and private sector entities that invest in infrastructure and operation of water systems and recover their costs through user fees.
Resilience	In the context of water resource system performance, the ability of systems to mitigate, adapt to, and recover from shocks and stresses in a manner that reduces chronic vulnerability and facilitates inclusive growth.
Risk	The potential for adverse consequences.
Shock	External short-term deviations from long-term trends that have substantial negative effects. Shocks can be a slow onset like drought or relatively rapid onset like flooding, disease outbreak, or market fluctuations (Sagara 2018).
Social-ecological systems	A term to emphasize the integrated concept of humans-in-nature that maintains that the delineation between social and natural systems is artificial and arbitrary (Berkes, Folke, and Colding 2000).

Term	Definition
Social inclusion	Social inclusion is achieved when all people, regardless of their sex, age, ethnicity, social status, income, religion, sexual orientation, ability, or disability, have the same rights and opportunities to contribute to and benefit from development efforts.
Source water	Sources (such as rivers, streams, lakes, reservoirs, springs, and groundwater) that provide water to public drinking water supplies and private wells.
Source water diversification	Development of alternative or additional water sources to supplement traditional water supplies and to leverage those sources to reduce water stress. Examples include using a mix of surface water and groundwater, employing desalination, or reusing treated wastewater.
Source water protection (SWP)	The protection of all present and potential future drinking water sources, including groundwater protection, wellhead protection, aquifer protection, and watershed protection pertaining to drinking water sources. Examples of SWP include nature-based solutions, such as reforestation and wetland conservation, as well as regulations, such as land use restrictions.
Stormwater treatment	Structural controls primarily designed to remove pollutants from stormwater runoff. Treated water can be used to supplement urban water supply.
Surface water	Any body of water found on the Earth's surface. This includes both saltwater in oceans and freshwater in rivers, streams, and lakes.
Urban water security	The dynamic capacity of the water system and water stakeholders to safeguard sustainable and equitable access to water for users. This includes adequate quantities of water of an acceptable quality. To be considered secure, this water should be continuously, physically, and legally available at an affordable cost for sustaining livelihoods, human well-being, and socio-economic development. Water supplies should be provided so as to ensure protection against water-borne pollution and water-related disasters and to preserve ecosystems in a climate of peace and political stability (Aboelnga et al. 2019).
Urban water supply	Water supplied to urban systems with the aim to provide continuous safe, clean drinking water. Urban water supply specifically refers to the source and raw water, with the associated infrastructure and governance tools needed to bring water to the city.
Vulnerability	The degree to which a system is susceptible to, and unable to cope with, adverse effects such as climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity (Intergovernmental Panel on Climate Change 2007).
Water recycling	The process of converting municipal or industrial wastewater into water that can be reused for a variety of purposes.
Watershed	A land area that channels rainfall and snowmelt to creeks, streams, and rivers and eventually to outflow points such as reservoirs, bays, and oceans.
Well	A hole drilled into the ground to access water contained in an aquifer.

PREFACE

The Urban Resilience by Building and Applying New Evidence in WASH (URBAN WASH) project is a centrally funded activity of the United States Agency for International Development (USAID) Bureau for Resilience and Food Security. It is a global five-year (2021–2026) research and learning program implemented by Tetra Tech. Collaborators include Aquaya Institute, FSG, Iris Group, SEGURA Consulting LLC, the Stockholm Environment Institute (SEI), and WaterAid. The project is led by a team of experienced researchers and urban WASH experts and supported by an external Advisory Board composed of water, sanitation, and hygiene (WASH) and urban resilience innovators and thought leaders.

The goal of the project is to promote impactful, sustainable, equitable, and climate-resilient WASH and water resources management (WRM) policy and programming in urban and peri-urban areas through strengthening evidence-based decision-making of partners and host governments at the local, regional, state, and national levels. To achieve this objective, the URBAN WASH project will perform tasks and complete deliverables under the following three interrelated components:

1. Component 1: Establish and support strategic engagement and partnerships to ensure local and broader relevance of research and use of evidence.
2. Component 2: Generate high-quality evidence through implementation research to increase the sector's understanding in three main areas:
   a. Enabling environment (i.e., viable urban WASH and WRM policies and regulations and institutional arrangements) for improved drinking water quality and city-wide sanitation;
   b. Approaches for sustainable small and informal service provision; and
   c. Sustainable approaches to improve source water protection and diversification for resilient water supplies.
3. Component 3: Provide on-demand technical assistance to USAID missions and technical bureaus to support urban WASH and WRM programming, including research, evaluations, and assessments.

Among URBAN WASH's first activities is the production and dissemination of in-depth desk reviews focusing on the enabling environment for improved water and sanitation provision, the role of small players in service provision, and source water protection and diversification.

EXECUTIVE SUMMARY

Climate change combined with rapid urbanization and economic development is increasing pressure on urban water supplies. While source water protection (SWP) and diversification of water sources have proven to be effective strategies to increase the resilience of water systems to these risks, many low- and middle-income countries (LMICs) have struggled to implement these actions.

This study aims to understand **what suite of SWP and diversification solutions can enhance the resilience of cities' water supplies and the constraints in their implementation** by examining successful examples, challenges and enablers of (1) planning, (2) negotiation across multiscale regulatory and institutional frameworks, and (3) financing models in cities in LMICs. The study team analyzed these topics via a literature review and case studies of seven cities that have documented policies and actions contributing to increased water security and resilience.

Source water protection is defined as the protection of present and potential future drinking water sources, including groundwater protection, wellhead protection, aquifer protection, and watershed conservation.

Diversification of water sources is defined as the development of alternative or additional water sources to supplement traditional water supplies and to leverage those sources to reduce water stress and increase resilience. Diversification measures can include both strategies to increase the supply of water and to address water demands.

KEY FINDINGS

This analysis highlighted successful SWP and diversification measures CWAs have put in place, the challenges CWAs in LMICs face with implementation and the enabling factors that could help to overcome them, and evidence gaps in the literature regarding these research questions.

Planning frameworks are needed to organize concepts, tools, and individuals to address the complexity and uncertainties of urban water supply systems. This review evaluated four planning frameworks that have been used successfully to incorporate SWP and diversification in water planning: Scenario Analysis, Robust Decision Support (RDS), Dynamic Adaptive Policy Pathways (DAPP), and Climate Risk-based Decision Analysis (CRIDA). While Scenario Analysis is the most used planning framework, it generally does not provide a robust consideration of the true range of uncertainties or stakeholder perspectives. DAPP techniques generally require experience with complex optimization methods and high computational capacity, which can make them inaccessible to low-resource contexts. Alternatively, CRIDA and RDS are better adapted to implementation in low-resource settings, as they were developed with these contexts in mind, and explicitly consider gender and social inclusion. However, even these tools require a relatively high level of technical knowledge and data availability, making them difficult to implement in low-resource contexts without external support. In addition, these frameworks do not always align with existing decision analysis and selection processes, hindering uptake of the approaches.

Although there are many analysis and modelling tools that can represent both city- and watershed-level conditions and changes, these **tools are often not well adapted to the technical capacity and governance systems in LMIC cities, and their use remains largely academic or driven by donors**. Often there is a lack of resources for data collection and management systems, or cities do not have access to the technical skills required to use these tools. Data monitoring and management systems that can be sustainably managed by local institutions are critical to sustained adoption of such tools. In addition, city authorities and utilities are typically dealing with chronic water service delivery challenges and often do not prioritize long-term planning until a crisis occurs. As a result of these challenges, LMICs in many cases have only undertaken SWP and diversification planning exercises as part of "projectized" activities driven by donor priorities or as part of research projects. Even when capacity building is provided, it is often short term or too generalized to incorporate the complexities of SWP and diversification scenarios. Overcoming these challenges is critical for developing well-informed solutions and providing accurate evidence to decision-makers and stakeholders.

Engagement of stakeholders in planning processes is crucial for developing socially, economically, and culturally appropriate and accessible plans for SWP and diversification. Collaborative planning exercises have been successful in creating interest among stakeholders in both high-resource and LMIC contexts, although in those cases it was often required by donors or driven by a crisis. However, there is a lack of practice and resources to support participatory planning and modeling. Stakeholder engagement is time-consuming and expensive, while the benefits are not well understood by many decision-makers, especially technical experts who generally rely on decision support systems developed for specific technical purposes.

Utilities typically must negotiate with institutions at the watershed or river basin scale to obtain or protect water sources. Cities' abilities to successfully advocate for their water needs depend on the size of the city, the legal-regulatory-institutional setting, and their ability to negotiate across a multiscale and complex institutional environment. Three negotiation methods that have proven successful within different institutional contexts and water rights regimes are: (1) incentivization; (2) trusted intermediaries; and (3) public buy-in. **Incentivization** may take the form of financial compensation or commitments around behaviors, such as demand reduction in exchange for access to additional water supplies. The use of **trusted intermediaries** is most often observed where there is a system of user-based water allocation and can help promote shared decision-making among stakeholders and ensure equitable representation of all voices. Gaining **public buy-in** has often been critical to obtaining acceptance of demand management and wastewater reuse measures.

The "best" set of financing alternatives for SWP and diversification for a particular city will depend on income levels, utility performance, and the local context. Efficiently run, profitable utilities, often in higher resource settings, are better able to implement tariff surcharges or access loans and bonds to fund SWP and diversification projects. Innovative financing mechanisms, such as payment for ecosystem services (PES)[1], can bring in new funding sources, including private sector contributions and interest income. Both PES and water funds require stakeholder trust, political commitment, clear expectations around the relatively long-time frames required to achieve results, and clear communication around costs and benefits. Different financing mechanisms are best suited to different types of projects. Large infrastructure projects, such as reservoirs, large pipelines, and wastewater treatment plants, are normally funded through loans, public-private partnerships (PPPs), national governments or through grants, while SWP is most effectively funded by PES or water funds.

RECOMMENDATIONS

This study identified key planning, negotiating, and financing strategies cities in LMICs have successfully used to implement SWP and diversification solutions. These three areas are interdependent and many of the challenges cities in LMICs face and enabling factors cut across the three research topics. Planning, negotiating, and financing all benefit from stakeholder engagement, and the earlier concerned entities are involved in the planning, the easier it is to negotiate with and obtain sustainable financing from relevant

[1] PES typically rewards those whose lands provide services, such as watershed protection and forest conservation, through in-kind or monetary payments by the beneficiaries of those environmental services.

stakeholders. Many of the successful examples of SWP and diversification have either been driven by a crisis or by donors, creating challenges for the sustainability of these measures.

For development partners who are aiming to support planning efforts to build more resilient urban water supply, it is critical to understand what institution is responsible for water allocation, what planning processes are in place, and what tools and data are currently used to inform those processes. Similarly, they must understand systems for water allocation or water tenure, as well as the relationships between competing stakeholders before working to support negotiations between water users. Development partners are often well suited to play a facilitative role by bringing together different stakeholders, bridging the gap between different water uses and different geographic scales, and identifying trusted intermediaries that can broker partnerships between competing water users.

For stakeholders aiming to mobilize finance for SWP and diversification, it is necessary to consider utility performance, governance systems, and the type of project when assessing different sources of financing. Utilities typically prioritize covering operations and maintenance costs and expanding services before protecting water resources, so partners should support utility performance and efficiency improvements before aiming to mobilize finance for SWP. Partners can support analysis of watershed management options to compare the costs and benefits of source water protection with other options.

FUTURE RESEARCH

Many of the key evidence gaps identified centered around similar topics, including the lack of prioritization of planning for uncertainty and implementing measures to address risks, the need for participatory engagement, and the importance of understanding and communicating trade-offs to stakeholders and decision-makers. The challenge is not that stakeholders do not know how to plan, negotiate, and finance robust diversified water supply plans, it is a lack of understanding of how to do so in LMICs where resources are limited. Much of the research available on this topic is from relatively larger cities or high-income contexts. An overarching evidence gap remains as to how CWAs in small- and medium-sized cities in LMICs can plan, negotiate, and finance SWP and diversification measures.

Table ES2. Themes and research questions for further research

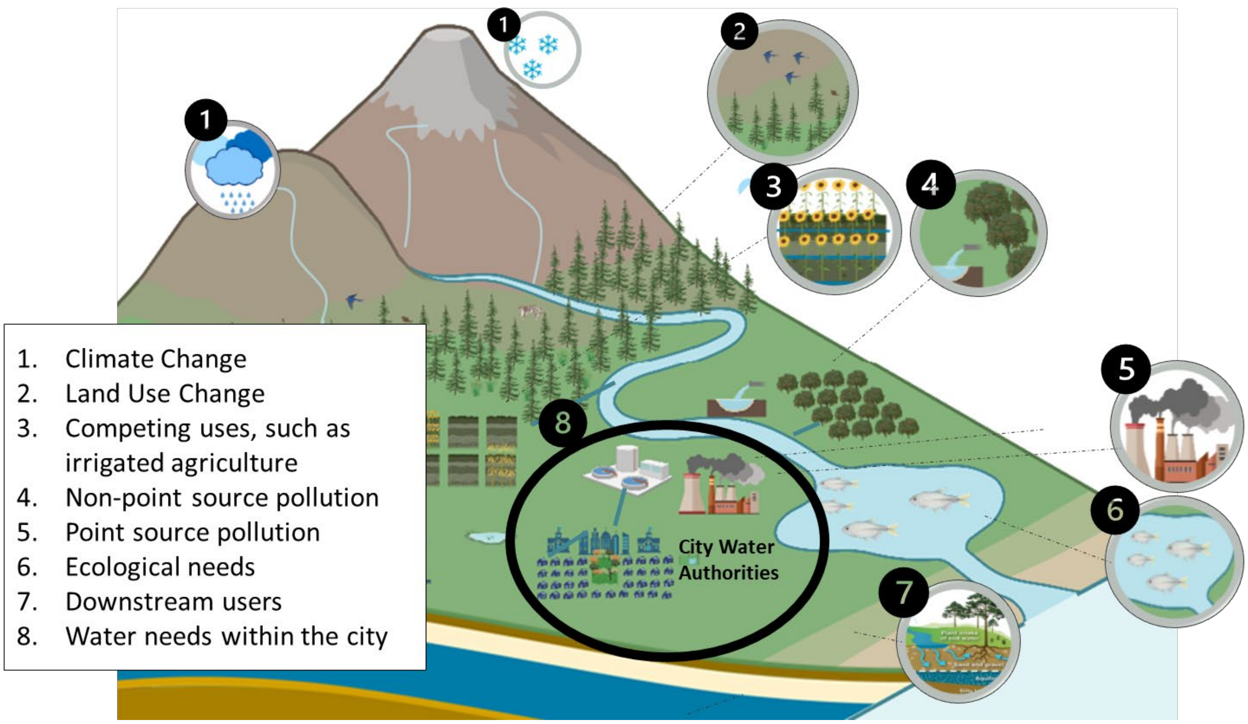
Theme	Research Question
Cross-cutting	What specific participatory processes for SWP or diversification are realistic and effective to implement in LMIC cities to promote equitable outcomes for marginalized groups, such as youth and women in source water contributing areas?
Planning	How can CWAs be motivated to consider risks to urban water supply systems and resilience strategies in their planning efforts?
	How can CWAs tailor existing tools and planning frameworks to evaluate SWP and diversification options effectively, given limited data availability and technical capacity?
Negotiation	How can incentive structures be set up in instances where finances are limited or when financial incentives may not be an option?
Finance	How can a CWA effectively quantify the costs and benefits of SWP and diversification projects to justify investment?
	How can LMIC cities structure water funds and other PES programs to maximize stakeholder support and benefits while avoiding challenges and pitfalls?
	What is the best combination of different finance sources to fund SWP and diversification?

1.0 INTRODUCTION

1.1 BACKGROUND AND MOTIVATION

Cities face a wide range of challenges related to water supply, including climate change, increasing demands for water, aging infrastructure, shifts in hydrologic regimes from rapid urbanization, and economic development needs. Globally, cities are expected to absorb population growth and rural migration (UN HABITAT 2020). One study estimates that by 2050, nearly one-half of the world's urban population will face water scarcity (He et al. 2021). Although cities and water authorities have always faced risks to water supply, these are rapidly changing (Abubakar and Gripenberg 2022; Corfee-Morlot et al. 2009; Miralles-Wilhelm et al. 2017; OECD 2011; Rijke et al. 2013; Romano and Akhmouch 2019; Vörösmarty et al. 2000). Figure 1 shows these challenges and how cities must negotiate across scales—from city to watershed to national and international levels when looking at climate change and shifting population dynamics.

Figure 1. Graphical representation of the challenges that city water authorities face at the watershed level



In the face of these widespread and diverse challenges, city water authorities (CWAs)—the institutions responsible for urban water supply—need to identify appropriate solutions to ensure water security, which requires resilience (the ability to withstand or recover from shocks). CWAs are often water utilities, but in some cases these are national or regional institutions, such as at the national level like the Rwanda Water Board or at the state level in Australia (see Appendix B for examples of CWAs).

In higher-income countries, source water protection (SWP) and diversification of city water supplies have proven to be effective strategies to increase urban water resilience. This is less true in low- and middle-income countries (LMICs). This desk review seeks to understand: (1) these successful approaches; (2) their potential applicability for LMICs; and (3) challenges and enablers for successful implementation and scaling in LMICs.

In summary, this study asks: **What suite of SWP and diversification solutions can enhance the resilience of cities' water supplies and what are the constraints in their implementation?** The focus of the research is understanding how cities—specifically CWAs in low-resource and low-capacity settings—can more effectively plan and adapt to a wide-ranging set of risks to achieve more resilient urban water systems through SWP and diversification.

To refine this overarching question, the research team conducted expert consultations and undertook an initial literature scan to identify key gaps and research needs. This scan identified various practical toolkits that broke down high-level water management approaches, like integrated water resources management (IWRM) and water security, into clear steps to assessing, planning, and implementing holistic water supply solutions. However, these broader toolkits provided little information on the specific constraints and enablers of SWP and diversification interventions beyond emphasizing the need for stakeholder-led and evidence-based processes to assess, plan, and implement viable and integrated solutions across scales.

Planning is the foundation for implementing SWP and diversification, and a key entry point for CWAs, making it important for those attempting to support cities to understand the practical tools needed, as well as the common challenges and enablers cities face in their planning processes. Yet, while theoretical guidance and best practices for planning exists, there has been limited research on how assessments and planning follow through to implementation (SWP 2021). Moving successfully from planning to implementation requires buy-in from a wide range of stakeholders, with many examples of failures to implement plans because of conflicts or lack of trust (Pohl 2014; UNECE, 2021). Literature cites a wide range of mechanisms, processes, and practices that can increase trust between actors in negotiations over shared waters (Grech-Madin et al. 2018; Tayia 2019). Yet much of this literature focuses on transboundary water allocation, and there are gaps in the evidence base for how cities can effectively negotiate with relevant stakeholders working at the watershed scale. Finally, while research has specifically focused on parts of the solutions—e.g., better modeling, participatory planning, and decision-making—there has been less research on how CWAs in LMICs can sustainably fund these plans.

Based on these identified gaps, the specific research questions (RQs) for this review are as follows:

> **RQ1:** *What types of plans, data tools, and capacities are necessary for cities and utilities to effectively adapt to climate change and other vulnerabilities to urban water supply?*
>
> **RQ2:** *How can water utilities and cities negotiate within multiscale regulatory and institutional frameworks to better advocate for and implement SWP and diversification?*
>
> **RQ3:** *What are viable and sustainable financing models for protecting source water and achieving resilient water supplies, and what are the factors that contribute to their success?*

1.2 STRUCTURE OF THE REPORT

This report starts with a summary of the definition and scope of the study, as well as a working definition for *urban water supply security*. It then presents the methodology the study team used to conduct the literature review and case studies (Section 2.0) and their findings (Section 3.0) in the form of successes, challenges for implementation in LMICs, and evidence gaps. Finally, the report ends with a conclusion that briefly synthesizes the findings and offers recommendations for future research (Section 4.0).

2.0 METHODOLOGY

This section outlines the methods used in conducting the desk review. First, Section 2.1 defines urban water supply security, source water protection, and diversification and describes how the team set the scope of the study. Section 2.2 and 2.3 present the literature review and in-depth case study analysis methodologies, respectively.

2.1 SETTING THE SCOPE FOR THE RESEARCH

While water security definitions and frameworks have varied widely in academic and applied research (Cook and Bakker 2012; Gerlak et al. 2018), Aboelnga et al.'s (2019, page 14) is the most cited definition **of urban water supply security**:

> "*The dynamic capacity of the water system and water stakeholders to safeguard sustainable and equitable access to adequate quantities and acceptable quality of water that is continuously, physically, and legally available at an affordable cost for sustaining livelihoods, human well-being, and socio-economic development; for ensuring protection against water-borne pollution and water-related disasters; and for preserving ecosystems in a climate of peace and political stability.*"

Given this definition of urban water supply security, there is an important scale dimension. Because most urban areas rely on water sources located outside the city, the definition of the urban water system and the associated scale must consider the entire "water footprint" (Hoekstra, Buurman, and Ginkel 2018) or the "reach of urban water infrastructure" (McDonald and Shemie 2014). Cities and other users in a watershed have a shared dependence on water resources outside their respective city or settlement limits, which requires an understanding of the trade-offs between competing water supply needs, including environmental requirements (Nel et al. 2017).

The boundaries of urban water supply are the watershed and/or aquifer boundaries on which a given city depends. This boundary is typically defined geographically by a line of highest elevation, or a ridge, that encompasses areas of lower elevation or the contributing area to an aquifer. In reality, boundaries are often informed by political as well as scientific choices and can lead to different accountability and management challenges within and between institutional actors (Cohen and Davidson 2011). To address this, this study includes consideration for governance structures both within and around cities to account for the political and social realities of various contexts and their impact on the urban water supply system.

This review focuses on the aspect of urban water security related to water supply as opposed to water delivery and wastewater collection: the dynamic capacity of the water system and water stakeholders to protect and diversify water supply within the city and in the broader watershed or aquifer. The **CWA** is the focal point for urban water supply security, as the institution responsible for ensuring adequate urban water supply.

2.2 LITERATURE REVIEW

An initial appraisal of the literature assisted in the clarification of the RQs. Following this initial review of literature on water security, urban water security, and approaches to examining these topics, the team completed a comprehensive review to understand the factors that hinder or contribute to successful SWP and/or diversification.

The team reviewed approximately 171 references, including both gray literature and peer-reviewed publications. The literature encompassed work focused on over 42 countries, with varying geographic scope—from the city level up to the global level. The literature reviewed included policy analyses, peer-reviewed journal articles, case studies, and other available publications identified through literature searches focused on urban water security and resilience, SWP, and diversification measures in LMICs. The databases included the Tufts University library system and Google Scholar. The search terms used included "urban water security," "source water protection," "source water diversification," "resilient urban water system," "urban water supply," "water financing," "financing source water protection," "payment for environmental services," and "diversified water portfolio." Sector experts shared additional sources in interviews. Appendix A offers a more detailed overview of the literature reviewed.

2.3 IN-DEPTH CASE STUDIES

The goal of conducting case studies was to further refine the factors for successful SWP and diversification by focusing on cities that exemplified some degree of success.

2.3.1 CRITERIA FOR CASE STUDY SELECTION

An initial literature review resulted in a list of 45 LMIC cities experiencing water supply security challenges, including cities in USAID priority countries. The criteria for selecting case study cities started with a sub-selection of those 45 LMIC cities that have documented policies and actions contributing to increased water security and resilience outcomes,, through existing and proposed diversification and SWP measures. The review used a set of relevant characteristics of the 45 cities to ensure a diversity of geographic, climatic, and demographic profiles among the final set of case study cities. Characteristics included geography, climate, income, city population, and growth rate (Bastin et al. 2019a; Central Intelligence Agency 2022; FAO 2012, 2018; World Bank 2020, 2022a). The team selected cities based on evidence of resilience in the face of a shock. In each case study, despite limitations, the cities were able to recover using SWP or diversification strategies. This selection process resulted in 16 shortlisted cities with a minimum of three cities selected each from Africa, Asia, and Latin America, and one from the Middle East, as shown in Table 1.

For the selected set of cities, the team conducted a qualitative analysis of city characteristics to ensure diversity and evaluation of the policies implemented for the shortlist (see Appendix A for full methods). The team included an assessment of the potential for replicability and sustainability, where *replicability* indicates interventions with the potential to be implemented in other cities globally and *sustainability* indicates interventions with the ability to be sustained into the future, based on availability of funds or acceptance among users. The seven cities the team chose for in-depth case studies (shown in Table 1 highlighted in blue) have implemented SWP and diversification methods that are potentially both replicable and sustainable.

Table 1. Quantitative characteristics considered for selection of final case study candidates, with selected cities highlighted in blue

Country	City	Geographic Region	Global Ecological Zone[a]	Population (Millions)[b]	Urban Growth Rate 2005–2020[c]	National Income Level[d]	National Water Stress in 2018[e]	Mean Annual Temperature (°C)[f]	Mean Annual Precipitation (mm)[f]
Ethiopia	**Addis Ababa**	Africa	Tropical mountain	4.60	4.0%	Low	32.3%	15.9	1,069
Ghana	**Accra**	Africa	Tropical dry forest	2.60	2.0%	Lower middle	6.3%	27.4	888
Kenya	**Nairobi**	Africa	Tropical mountain	5.12	3.8%	Lower middle	33.2%	18.6	1,029
Mozambique	**Maputo**	Africa	Tropical moist forest	1.10	0.2%	Low	1.75%	22.9	774
South Africa	**Cape Town**	Africa	Subtropical dry forest	4.80	2.5%	Upper middle	63.6%	17.4	560
Zambia	**Lusaka**	Africa	Tropical dry forest	3.04	4.8%	Lower middle	2.80%	20.5	869
Cambodia	**Phnom Penh**	Asia	Tropical dry forest	2.21	3.0%	Lower middle	1.0%	28.3	1,402
India	**Delhi**	Asia	Tropical shrubland	32.07	3.2%	Lower middle	66.5%	25.0	729
Philippines	**Manila**	Asia	Tropical moist forest	14.41	1.7%	Lower middle	28.7%	27.4	2,266
Bolivia	**La Paz**	Latin America	Tropical mountain	1.91	1.3%	Lower middle	1.2%	9.9	675
Brazil	**São Paulo**	Latin America	Tropical rainforest	22.43	1.3%	Upper middle	1.4%	19.0	1,487
Colombia	**Bogotá**	Latin America	Tropical mountain	0.20	2.7%	Upper middle	4.2%	14.0	1,866
Ecuador	**Quito**	Latin America	Tropical mountain	1.93	1.6%	Upper middle	6.8%	13.6	1,116
Guatemala	**Ciudad de Guatemala**	Latin America	Tropical moist forest	3.00	1.6%	Upper middle	5.7%	20.0	1,254
Peru	**Arequipa**	Latin America	Tropical mountain	0.95	1.6%	Upper middle	6.6%	15.4	58
Jordan	**Amman**	Middle East	Subtropical mountain	2.21	4.5%	Upper middle	100.0%	16.9	306

[a] Source: FAO 2012
[b] Source: Central Intelligence Agency 2022
[c] Average annual rate of change by city. Source: UN 2018
[d] Source: World Bank 2020
[e] Water stress is defined as the proportion of available freshwater resources being withdrawn (ratio between total freshwater withdrawn and total renewable freshwater resources, after accounting for environmental flow requirements). Source: FAO 2018
[f] Source: Bastin et al. 2019a, 2019b

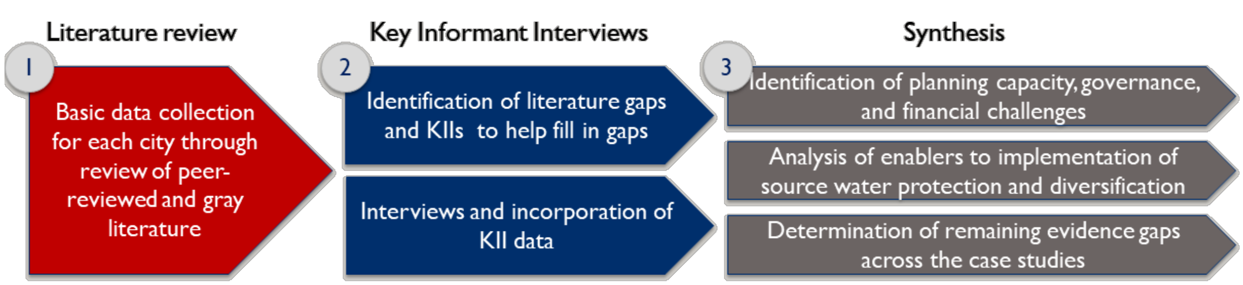
2.3.2 CASE STUDY ANALYSIS AND FINDINGS

For the case study analysis, the team collected data through a targeted literature review for each city in combination with key informant interviews (KIIs). The types of data collected include basic background data, governance, and financial context (see Table 2), as well as lessons learned related to the three RQs. The study team used KIIs with experts from different institutions, including academia, government, and civil society, to complement and validate data from the literature review. A summary of the methodological approach is illustrated in Figure 2.

Table 2. Examples of topics examined for each case study city

Theme	Data Collected
Biophysical context	Biophysical setting
	Population and growth rate
	Climate considerations (e.g., precipitation patterns, temperature)
	Watershed characteristics
	Climatic risks faced (i.e., drought, flooding)
Planning capacity	Existence of water balance or other data tool
	Existence of risk framework and what risks were considered
	Engagement of stakeholders in informing baseline conditions
	Technical staff capabilities
Governance/negotiation	Key actors and power dynamics
	Regulatory constraints
	Extent to which governance was considered in proposed solutions
	Existence of trade-off analysis and what aspects are included
	Degree of stakeholder engagement and buy-in
	Effectiveness of communication modalities used to inform trade-offs to stakeholders
	Methods used for solution evaluation (i.e., policy options, infrastructure plans)
Finance	Methods used to obtain financing and its level of sustainability
	Level of stakeholder engagement in implementation; level of stakeholder buy-in for implementation
	Extent to which solution implementation was incremental
	Extent to which solutions were adaptive
	Financial constraints
	Financing mechanisms considered/utilized

Figure 2. Case study methodological approach



3.0 FINDINGS FROM THE LITERATURE REVIEW AND CASE STUDY SYNTHESIS

The findings for each of the three research questions are provided in the following subsections. Appendix C includes a summary of the successful SWP and diversification measures that were identified through the literature review and case studies.

3.1 PLANNING FOR RESILIENT URBAN WATER SUPPLY

CWAs must undertake risk-based planning to be able to identify the diversification and SWP options that will provide resilient water supply in the face of hydrologic, economic, and socio-political uncertainty. A combination of data tools and capacities are needed to successfully implement these planning processes. This section, therefore, focuses on the research question:

What types of plans, data tools, and capacities are necessary for cities and utilities to effectively adapt to climate change and other vulnerabilities to urban water supply?

3.1.1 SUCCESSFUL URBAN WATER SUPPLY PLANNING

The complexity of urban water systems and the uncertainties associated with climate change, urbanization, and other risks result in a need for a unifying planning framework with which to organize concepts, tools, and individuals (SWP 2018; Vicuña et al. 2018). CWAs need "stronger climate-risk analysis to better direct policy efforts, mitigation and adaptation approaches, and to attract financing," which requires an understanding of the frameworks, data systems and analysis tools that are best suited for CWAs in LMICs (GWP and UNICEF 2022). Since water and human systems are intertwined, it is crucial that planning processes consider impacts on the most vulnerable and underprivileged social groups (Akamani 2016; Savenije 2009; Wesselink, Kooy, and Warner 2017).

Participatory Planning

The engagement of stakeholders in planning processes is crucial for developing socially, economically, and culturally appropriate and accessible multiscale planning frameworks that promote the development of successful SWP and diversification solutions (Jordan et al. 2018; Pahl-Wostl et al. 2007; van Bruggen, Nikolic, and Kwakkel 2019). Sociocultural contexts and community participation play key roles in knowledge collection and definition of existing and future water uses. Collaborative planning, particularly in the form of co-creating watershed-level management plans, has been shown to result in more equitable outcomes and more resilient bulk water supply (Vicuña et al. 2018). Thus, it is important to understand which participatory methods are most successful in encouraging these positive outcomes.

There is extensive literature on effectively engaging stakeholders in water planning, particularly in high-resource settings. Engagement strategies range from simply informing stakeholders to consulting the public to gaining feedback to collaborating to develop solutions to fully empowering the public in decision-making, with different levels of cost and capacity associated with each (Langsdale and Cardwell 2022).

Collaborative planning exercises have been successful in creating interest among stakeholders in both high resource and LMIC contexts (see Box 3). Under the Cape Town Water Strategy (2019), the city has implemented multi-stakeholder participation in its water sector initiatives as a key pillar, including community visits and interviews to ensure local water-related needs are understood and all Cape Town residents have access to safe water (Water and Sanitation Department 2019). This stakeholder engagement gives specific attention to residents of informal settlements and gathers their input on lived experiences as it pertains to water access, then integrates findings into the city's approach to providing water access to these communities. In a review of Australian case studies, interaction between the development team and the user, good relationships and trust, open and transparent communication, and early critical thinking about the problem and role of the model in problem solving were found to be key to successful participation in integrated modeling projects (Merritt et al. 2017).

Common Planning Frameworks for Resilience

Planning frameworks that address climate and other uncertainties require integration across multiple domains to effectively account for complex, interacting factors, including integration across stakeholders, systems and models, disciplines, and scales (Kelly [Letcher] et al. 2013). While there are many overlapping planning frameworks that have been proposed within the environmental resources and urban water supply fields, this review focuses on four frameworks that have had broad attention and uptake with examples in LMICs, especially within the climate uncertainty context: Scenario Analysis, Robust Decision Support (RDS), Dynamic Adaptive Policy Pathways (DAPP), and Climate Risk-based Decision Analysis (CRIDA) (see summary in Table 3).

Scenario analysis is a process of exploring and evaluating alternative future outcomes for a system or situation by constructing and analyzing a range of plausible and internally consistent scenarios that incorporate uncertainties and assumptions, and considering their implications for decision-making (Mahmoud et al. 2009). The formal approach described by Liu et al. (2008) comprises five phases of scenario development: scenario definition, construction, analysis, assessment, and risk management. Scenario analysis represents the most general framework of the four and is usually implemented with a few simple scenarios, such as high and low population growth or high and low streamflow or precipitation. This framework is thus accessible for practitioners who often use a scenario approach in decision-making processes already, making it very widely used by CWAs; however, the simplistic representation of uncertainties and lack of universally defined participatory methods can reduce the robustness of the findings from such planning. Since the framework is limited to the generation of scenarios and does not provide guidance on evaluation of potential solutions, the scenario analysis framework can be helpful to identify risks but does not necessarily enable CWAs to develop solutions that will be resilient to climate and other uncertainties into the future.

The ***RDS framework*** combines the robust decision-making method with a participatory water resource planning framework to inform long-term policy under uncertainty (Purkey et al. 2018). The RDS approach engages stakeholders throughout the planning process, starting with an understanding of critical uncertainties (X), proposed solutions (L), the problem space (R), and stakeholders' metrics of success (M), often abbreviated at the "XLRM" method (Lempert et al. 2006). This framework generally employs the use of numerical models to simulate future conditions, which can show the degree to which proposed strategies can or cannot meet the desired levels of reliability but may be a hurdle for CWAs that do not have the necessary knowledge of modeling methods or computing resources to carry out such simulations. Stakeholders can then consider new and combined strategies and see the impacts, not only on their own metrics, but the metrics across all stakeholders. This results in a common or shared understanding of the problem and solutions, reducing conflict around plans for implementation. In California, planners used RDS to develop a conceptual model of the Yuba River system through collaborative methods that proved valuable in finding solutions among diverse stakeholders, including groups that often have opposing interests, such as farmers and environmentalists (Stockholm Environment Institute [SEI] 2019). Finally, as part of the implementation and development of RDS over time, there have been a number of efforts to explicitly address the role of gender and social equality issues that may arise when using the RDS framework (Escobar et al. 2017).

Box 1. Robust Decision Support (RDS) in Quito, Ecuador

In Quito, an RDS process completed in 2021 analyzed the vulnerability and resilience of the water system to future uncertainties, including climate change, catastrophic pipeline failure events, ecological flow requirements, and growth in the number of users; the analysis compared system vulnerabilities under different management scenarios, including scenarios where per capita water consumption and leakage were reduced. Results of the vulnerability analysis were used to inform the water system master plan (SEI 2021).

Additionally, as part of the Cotopaxi contingency plan, led by the National Risk Management Secretariat, the utility's proactive risk assessment approach has included the use of modeling. The risk management unit head at the *Empresa Publica Municipal de Agua Potable y Saneamiento of Quito* emphasized the importance of risk assessment tools that quantify risks and impacts to allow decision-makers to consider risk reduction costs explicitly rather than implicitly (KI Quito 2022a). Using these tools, the utility has taken several steps to build system resiliency, including building infrastructure to reroute water supplies affected by catastrophic events.

CRIDA is a framework that provides guidance on how to design, implement, and evaluate adaptation measures to address water scarcity in the context of changing climate conditions, while taking into account the needs and perspectives of different stakeholders (Guillermo et al. 2018). It is a participatory and iterative process that involves the identification of vulnerabilities and risks, the development of adaptation options, and the evaluation of their feasibility, effectiveness, and sustainability. The newest of the four frameworks introduced here, CRIDA has had rapid uptake and dissemination as it was developed specifically for global implementation by UNESCO (UNESCO 2020). CRIDA has had a number of successes in both high-resource (e.g., State Water Project in California, Limari River basin in Chile) and LMIC applications (Box 2) (UNESCO 2020; Verbist et al. 2020). In Zambia, a retrospective analysis of investments at a water treatment plant demonstrated the efficacy of CRIDA in a data-limited environment and highlighted the potential for significant performance benefits from small, up-front investments in flexibility, while also providing the opportunity to test and adapt the innovative, data-driven tool for decision-making (Lawson 2019). One limitation of CRIDA is that it is the only framework of those reviewed that focuses specifically on climate as the main overarching uncertainty, while the other four are framed around uncertainties more generally, which can include legislative, economic, demographic, and ecological uncertainties (Manous and Stakhiv 2021).

Box 2. Climate Risk-based Decision Analysis (CRIDA) in Bangkok, Thailand

In Bangkok, Thailand, researchers from the Asian Institute of Technology worked with Metropolitan Waterworks Authority to demonstrate the application of CRIDA, which uses a combined top-down and bottom-up approach, to (1) identify critical thresholds that impact the system's performance, (2) determine system vulnerabilities through a stress test (scenario analysis), and (3) identify feasible diversification options. As in many low-resource contexts, this study used a modified version of the CRIDA framework adapted to areas where there is no existing model of the system, and data limitation is a challenge. They substituted a statistical model for a simulation model to stress test the system. Stress tests were conducted by adjusting input variables assuming a wide range of possible future climatic conditions. Reasonable adaptation actions were then evaluated based on the plausibility of occurrence of the future test scenarios. Diversification actions identified based on the stress test included transferring raw water from the Mae Klong river basin, shifting the raw water intake upstream to reduce the effects of saltwater intrusion from the Gulf of Thailand, and seawater desalination.

DAPP addresses complex and uncertain problems that involve high levels of ambiguity, incomplete information, and divergent values among stakeholders (Marchau et al. 2019). Like RDS and CRIDA, DAPP uses scenario-based analysis, robust decision-making, and iterative learning; however, it distinguishes itself by explicitly considering decision-making over time by exploring alternative sequences of solutions according to many possible futures (Marchau et al. 2019). In an example in Portugal, a modeling effort led by external researchers allowed stakeholders to create a supply portfolio that prioritized a strong preference for incremental and distributed small-scale measures (e.g., water use efficiency, landscape water retention), while addressing potential failure of such policies with the option of a desalination plant (Dias et al. 2020). However, DAPP has mostly been employed in the evaluation of flood risk management infrastructure investment and portfolio management in high-resource settings, with limited applications in water supply and low-resource applications (Bosomworth and Gaillard 2019; Lawrence and Haasnoot 2017; Trindade, Reed, and Characklis 2019).

Table 3. Planning frameworks to address climate change and other uncertainties in the development of water supply management plans

Framework	Technical Needs	Participatory Approach	Strengths	Weaknesses
Scenario Analysis	Low	Not necessary; usually participation from CWA technical experts in generation of scenarios and proposed solutions	Allows for simple storylines that can easily be understood by a range of stakeholders	Not well suited to deep uncertainties, such as climate change
RDS	Medium	Participatory approach outlined for CWA and stakeholders during formulation of problem, metrics of success, critical uncertainties, and proposed solutions	Strong focus on deep uncertainty and stakeholder engagement	Results can be complex and require visualization for all stakeholders to access and understand
CRIDA	Medium	Participatory approach outlined for CWA and stakeholders, with bottom-up approach to the design of the analysis and interaction with a trained analyst encouraged	Sensitive to indigenous and gender-related water vulnerabilities	Singular focus on climate change as the overarching uncertainty
DAPP	High	Iterative participatory approach outlined for CWA and stakeholders, but with implementation of modeling and analyses using advanced optimization methods generally by a trained analyst	Inclusive of stakeholders and allows for climate change among many uncertainty analyses	Results are complex, requiring interpretation by trained analysts

Overall, many implementations of these planning frameworks were conducted to produce a climate or water plan required at regional, state, or national levels, as in the example of Quito (see Box 1). Engaging relevant stakeholders in the early stages of planning, so that buy-in can be gained early in the process, was important in ensuring that outputs from these planning processes translate into a plan that can be successfully implemented.

Modeling and Analysis Tools

The application of these planning frameworks requires modeling tools to understand the tradeoffs and synergies of different SWP and diversification options in the face of climate change and other deep uncertainties. Cross-scalar modeling tools that represent both city- and watershed-level conditions and changes are required to capture the complexity and dynamics of the water system. For example, hydrologic modeling capabilities, which couple the influences of human activity with terrestrial water fluxes, can clarify large-scale impacts to water supply (Wada et al. 2017). Examples of uncertain city-level system fluxes are leaks in water distribution systems, wastewater treatment and reuse, and domestic rainwater catchment. Examples of uncertain watershed-scale boundary conditions are dynamic basin-wide rainfall-runoff, evapotranspiration, land use changes, upstream diversions and geologic characteristics (Galaz 2007; van den Brandeler, Gupta, and Hordijk 2019). These system fluxes and boundary conditions can be simulated using a number of basin analysis tools that enable decision-makers to assess the impact of interventions on the water supply system, including (SWP 2018):

Box 1. Decision-scaling Using WEAP in Lusaka, Zambia

The decision-scaling approach connected the bottom-up process of collaborative model development with the top-down process of incorporating climate and socio-economic information to investigate the risks for water supply to the City of Lusaka (Ilunga and Cullis 2020). Information on critical water security issues were explored during a series of City Learning Labs held with key stakeholders. Two WEAP models were developed: 1) a simple model of the Lusaka water supply system integrating both surface and groundwater supply options, and 2) an expanded city-region water resources model that included critical parts of the Kafue River basin that impact both water and energy availability for Lusaka. The combination of the two models allowed for a better understanding of the uncertainty inherent in the results, showing both low and medium risks depending on the model. Additionally, these data tools allowed for disaggregation of risk by sector, allowing for the development of demand management or adaptation options for these sectors and determined that socio-economic uncertainties posed greater risks to the system than climate uncertainties.

1. Hydrologic models: Simulate aspects of the hydrologic cycle that occur at the catchment level, including evapotranspiration, precipitation, rainfall-runoff, infiltration into groundwater, and interactions between water bodies (lakes, rivers, tributaries, etc.).
2. Flow routing models: Simulate the timing and magnitude of flow throughout the watershed to predict where flooding and peak flows may occur.
3. Operational models: Simulate how infrastructure and policies in the watershed (e.g., dams, weirs, diversions, distribution networks) are operated to help determine which strategies or conditions result in optimal water use.
4. Agricultural production models: Simulate the yield response of crops to water availability and changes in water use depending on crop decisions.
5. Hydro-economic models: Simulate water allocation and management based on the price of water to determine the optimal allocation according to stated goals or values.
6. Water quality models: Simulate the transport and fate of contaminants in the water supply system, helping to identify sources of contamination and the impact of interventions on water quality.
7. Groundwater models: Simulate groundwater flow within aquifers, which may include contaminant transport, to understand the interactions between surface water and groundwater and long-term sustainability of groundwater use.

The choice of modeling tool will depend on the local context of the city, other users of water, and existing and potential water sources. If the city is groundwater dependent, MODFLOW would be among the most useful tools, while if there are upstream mines, a surface water quality tool might be needed.

There are thousands of tools developed globally, many of which are site-specific. While these tools can be useful, they typically are not easily transferrable. Therefore, this analysis only considers those tools that can be applied more generically. To develop evidence-based plans that incorporate SWP and diversification, a minimum set of criteria include the ability to represent:

- The hydrology under changing climate (i.e., the availability of water); and
- Current and projected future use of water based on water system operations and water management (i.e., the allocation of water).

Ideally, both would be included in a single tool. There are a number of fully integrated modeling tools like MIKE (MIKE 2023) and WEAP (Sieber 2022) that rely mainly on internal simulation and optimization programs that address a number of modeling tool needs. These modeling tools vary widely in their services and abilities, with a wide range of data requirements and flexibility (see Table 4). For example, WEAP, MIKE+, and Automated Geospatial Watershed Assessment (AGWA) all allow for the identification of scenarios according to multiple dimensions of uncertainty for easier visualization and analysis. Additionally, some platforms allow for coupling with other non-water model types, such as WEAP, which can connect with the energy modeling platform LEAP that allows for simultaneous optimization of energy and water needs in hydropower contexts (Heaps et al. 2012; Liu et al. 2021), or SWAT, which can link to the geospatial Water Ecosystems Tool (QWET).

Several software tools exist that include multiple basin analysis tools that can be linked but take more advanced skills to do so. In some examples, they are separate tools within a large toolkit hosted by a single organization, as in the case of Hydrologic Engineering Center (HEC) (HEC Software 2023) and SERVIR (Asian Disaster Preparedness Center 2023). Other tools are centered around a geographic information system (GIS) platform that process geospatial data into existing modeling tools, such as AGWA (AGWA 2015), which relies on the U.S. Department of Agriculture's Kinematic Runoff and Erosion Model (KINEROS), Rangeland Hydrology and Erosion Model (RHEM), and the Soil and Water Assessment Tool (SWAT), or Free and Open Source Software Tools for Water Resource Management (FREEWAT) (FREEWAT 2019), which incorporates a majority of the U.S. Geologic Survey's groundwater modeling software MODFLOW's modules.

In the case of some modeling software, use remains largely academic or outside of the realm of CWA analyses, particularly in the case of GIS platforms created to facilitate the use of better known, but sometimes more difficult to use, software. For example, this study was unable to find implementation of AGWA, which is a newer and lesser-known platform, for urban applications in LMICs and no examples of its application in policy or planning (Baker and Miller 2013; Baldyga et al. 2005; Yousif et al. 2022). Alternatively, SWAT, a main foundational software within AGWA, is well known and used in many SWP projects worldwide on its own (Hunink et al. 2013) or as a component in integrated modeling software, such as WEAP (Touch et al. 2020) or MIKE (Mohajeri et al. 2016). Similarly, HEC has broad use on its own and in conjunction with other tools (Box 4).

Box 2. Modeling Tools in São Paulo

Cho et al. (2023) conducted a multi-year collaborative watershed modeling effort in the Cantareira watershed that supplies São Paulo, Brazil. The effort promoted stakeholder engagement in the planning and development of nature-based source water protection projects in the face of multiple water crises resulting from drought in 2014 and 2018. Researchers began with an existing single-event focused Hydrological Engineering Centre-Hydrologic Modeling System (HEC-HMS) model developed by stakeholders and converted the model into a long-term planning tool. The external research team added modeling capabilities from SWAT and two other environmental modeling software to represent the implementation of riparian and forest protection measures and their impacts to water supply. By adapting the existing model for the needs of the planning framework, the project could be managed by existing CWA resources.

Table 4. Modeling tools used for water planning

Modeling Tool	Basin Analysis Tools							Cost	Technical Capacity Required	Ability to Look at Water Availability and Allocation Jointly	Implementation
	Hydrologic	Flow Routing	Operational	Agricultural Production	Hydro-economic	Water Quality	Groundwater				
Automated Geospatial Watershed Assessment (AGWA)[2]	•	•						Free, but requires "Basic" ArcGIS license	Varies depending on model	No	(Baker and Miller 2013)
Free and Open Source Software Tools for Water Resource Mgmt (FREEWAT)[3]	•		•	•		•	•	Free	High	No	(De Filippis et al. 2020)
Hydrologic Engineering Center (HEC)[4]	•	•	•		•	•		Free	High	No	(Cho et al. 2023; Mounir et al. 2019; Paraiso, Del Castillo, and Vicente 2020; Zeng et al. 2012)
MIKE+ (e.g., HYDRO Basin, FLOOD, SHE, FEFLOW)	•	•	•			•	•	High	High	Yes	(Mohajeri et al. 2016)
SERVIR Decision Support Tools	•	•	•	•			•	Free	Low	No	(SERVIR Global 2021)
Soil Water Assessment Tool (SWAT)	•			•		•	•	Free	High	No	(Hunink et al. 2013; Mohajeri et al. 2016; Touch et al. 2020)
Water Evaluation and Planning (WEAP)	•	•	•	•	•	•	•	Free for developing countries	Varies based on data availability	Yes	(Forni et al. 2016; Ilunga and Cullis 2020; Touch et al. 2020)

2 Uses U.S. Department of Agriculture software.

3 Uses USGS MODFLOW programs.

4 Includes all HEC programs (e.g., RAS, HMS, ResSim, WAT).

Data for Planning

To leverage these and other planning frameworks, CWAs require the technical capacity to collect, manage, and use data for simulation, analysis, and visualization, including data on water supply and demand, competing water uses, climate trends, and ecosystems(Mason & Calow, 2012). At the start of a planning process, CWAs need to develop and measure reliable and relevant metrics and indicators to ensure shared understanding of water supply risks and to simulate future scenarios to plan for uncertainties (Matthews et al. 2019; Rees 2006). Planning bodies can rely on watershed-level indicators, such as those proposed by the UN Water Task Force on Indicators, Monitoring, and Reporting, as well as city-specific indicators (Garrick and Hall 2014; Vanham et al. 2018).

Regardless of the choice of tools, all require a minimum amount of data about the local context to provide actionable information, as well as data to allow for calibration to historical conditions. Increasingly there are global data sets freely available where there are data gaps; however, these datasets may have significant biases or low resolution in the area of study. With additional local data, it is possible to provide much more tailored and accurate representations of the watershed and water supply system, and generally, the more data that is available, the more case specific the output will be to inform decision-making. Further details of standard data requirements are provided in Appendix D. Investment in data monitoring and management systems that can be sustainably managed by local institutions is critical to enabling cities and utilities to effectively plan.

To implement a model that combines basic hydrology and water management/operations, the following data would ideally be provided (Sieber, 2022):

Water Availability:

- Maps of river networks with catchment boundaries and digital elevation models (DEM)
  - Use for disaggregating sub-basins based on elevation, slope, and/or aspect
  - Publicly available from sources such as the global runoff data center and Hydrosheds[5]
- Precipitation, temperature, relative humidity, and wind
  - Historical time-series data from local stations covering same time period needed to calibrate the model
  - Available from a variety of sites including Climate Research Unit data available from the World Bank[6,7]
- GIS shapefile of land cover/land use
  - Necessary when considering land conversion scenarios.
  - Publicly available global datasets are available from the European Space Agency
- GIS shapefile of soil type
  - Disaggregating based on soil type may be done when evaluating soil erosion
  - Available from FAO
- Time-series of observed streamflow
  - Ideally measured locally for 10-30 years, including wet and dry years, at points upstream of existing or proposed major diversions or reservoirs
- Reference evapotranspiration

[5] Publicly available global datasets are not commonly available on a grid smaller than 3 seconds (90 meters), so local maps are needed for areas smaller than 10 km^2

[6] Resolution of the data and the time frames for which it is available vary. Local data is valuable when available.

[7] Historical time-series climate data obtained from local stations should all cover same time period in order to calibrate the model.

- Available from global data sets, such as WAPOR, FAO's data set for Africa and the Near East

Water Allocation:

- Water demands for households, commercial, industrial, and public users (historic and projected future demand[8]):
  - Number of people/users,
  - Per capita water use rate or per unit of industrial output,Water use variation throughout the year, and
  - Percent of water returned to system (water that is not "consumed" may return directly to surface water or groundwater or to wastewater treatment plant).
- Water demands for agriculture
  - Data needs vary based on how agriculture is modeled (see Appendix D for additional data)
- Ecological flow requirements, including timing and volume
- Infrastructure:
  - Dam and reservoir locations, physical data (volume-elevation curve), and historical volume data
  - Water and wastewater treatment plants and reuse (capacities, volumes treated)),
  - Water distribution network (capacities and location (capacities, connections, and historical flows /volumes distributed)

Data management can be just as valuable as data collection itself, including the creation of better platforms to house existing data and data-sharing programs between sectors, stakeholders, agencies, and even governments (Matthews et al. 2019; Rees 2006) (Box 5). One example of a successful data warehouse is that hosted by the Consortium of Universities for the Advancement of Hydrologic Science, which has evolved from a database for study-generated models and data to an integrated modeling platform that can leverage such data (Peckham and Goodall 2013; Tarboton et al. 2014). Such user-focused platforms can be incredibly valuable, as research has shown that decision-driven data systems that take into account the needs of both producers of data and users of data reduce inefficiencies and inequities that can be caused by lack of data or poor organization of existing data (Cantor et al. 2021).

Box 3. Data Management Systems in São Paulo, Brazil

In São Paulo, the National Water Agency (*Agência Nacional de Águas e Saneamento Básico* or ANA) provides data in an online platform on water demands, water supply, and water security by state and by municipality through the Atlas Águas (ANA 2022). Similarly, spatial environmental data for the State of São Paulo is available on the DataGEO platform (State of São Paulo 2022), and hydrologic data for the RMSP is available through the Sabesp-hosted Water Sources Portal (Portal dos Mananciais), which has up-to-date and historical data for rainfall, streamflow, and reservoir levels for water supply system (Sabesp 2022). Finally, the Piracicaba, Capivari, and Jundiaí (PCJ) River Basin Agency, the watershed support institution of the main source water basin for the city, hosts the PCJ Basin Decision Support System, which houses maps, monitoring data, and modeling results for use by the general public and decision-makers (PCJ River Basin Agency 2023).

3.1.2 PLANNING CHALLENGES AND ENABLING FACTORS FOR SUCCESS

CWAs in LMICs face unique challenges that make the above frameworks and tools difficult to implement. Overcoming these challenges is critical for developing well-informed solutions and providing

[8] Usually modeled using population and per capita water use rates, accounting for annual water use variations.

accurate evidence to decision-makers and stakeholders. Some challenges that are apparent across many LMICs include: (1) planning frameworks are not adapted for the technical capacity and governance of LMICs; (2) cities lack resources for monitoring and data collection tools and therefore often rely on outdated information; (3) CWAs are unable to prioritize long-term planning until a crisis occurs; and (4) constraints to implementing participatory approaches limit the applicability of planning processes. Given the diversity of cities in the case study analysis and literature review, specific solutions varied; however, some enabling factors emerged for how the cities addressed challenges.

Planning frameworks are not adapted to the technical capacity and governance systems in LMICs

Many of the planning frameworks discussed above were developed in high-resource contexts with the necessary technical knowledge and data availability, making them difficult to implement in low-resource contexts. Lack of user-friendliness and training requirements present a barrier to the adoption of specialized frameworks (Kuller et al. 2018). For example, DAPP has experienced difficulties in uptake for decision-making because of the cognitive and resource requirements, such as high-powered computing equipment, knowledge of optimization methods, and programming skills in specialized packages and programs. Additionally, attempts at implementation of DAPP have shown that established systems of governance within CWAs have existing decision analysis and selection processes that do not easily accept the approaches that define DAPP mainly due to a lack of experience in complex systems framing (Stanton and Roelich 2021). Alternatively, in some cases, a CWA may have some technical capacity but lack experience in more advanced modeling approaches, as in the case of the Rajshahi City Corporation, which partnered with academic collaborators to carry out a groundwater study using MODFLOW, but with a lack of SWP or water diversification alternatives and no consideration of future uncertainties (Haque et al. 2012).

Stanton and Roelich (2021) suggest a number of paths to wider applicability of planning frameworks, including the implementation of more **qualitative methods** to replace cumbersome quantitative methods, and allowing for more **flexibility in the methodological choices**, elements, or techniques that users can incorporate depending on their needs (Stanton and Roelich 2021). Variations of this type of flexibility were achieved in Karnataka, India, where stakeholders collaboratively developed adaptation pathways that were then evaluated according to collectively determined metrics under future climate and socioeconomic uncertainty using WEAP (Bhave et al. 2018). In that case, researchers developed a quantitative model and then worked through iterative workshops to modify and expand the representation of the model to match stakeholder expert knowledge of the problem and potential diversification and SWP solutions, including urban greywater and stormwater reuse, demand management, and lake restoration. In addition, interaction between the development team and the user, good relationships and trust, open and transparent communication, and critical thinking early about the problem and role of the model in problem solving have been found to build acceptance of model results, making them a key to the success of integrated modeling projects (Merritt et al. 2017).

To build robust planning capacity, the literature points to the effectiveness of **tailored training programs** that are specific to the needs and context of a given CWA and that prioritize continuous monitoring and iteration for longevity as an effective enabler (Ferrero et al. 2019). Ferrero et al. (2019) found a number of successful components to capacity building by reviewing global implementation of water safety plans (WSPs), including training using a diverse set of tools (lectures, case studies, role play, on-the-job instruction) provided by local actors, peer-to-peer learning, and a program champion to promote long-term uptake. Such training programs need to consider the **inclusion of women and marginalized groups**, who are often underrepresented in technical and decision-making roles (Buechler and Hanson 2015). In the Hindu Kush Himalaya region, one study found that capacity-building workshops to improve geospatial skills among local practitioners were underattended by women, particularly on-the-job trainings, where 91% of attendees were men (Tripathi and Thapa 2019).

Limited resources for data collection and management systems

CWAs often lack the required data to accurately assess risks and inform plans. At the same time, they also often do not have the resources or capacity to invest in longer-term monitoring systems that can measure the effectiveness of SWP and diversification solutions and enable dynamic adaptation to plans.

When CWAs lack data to inform plans, they may rely on outdated information or assumptions and cannot appropriately account for uncertainty, leading to sub-optimal planning processes and an inability to accurately assess options for SWP and diversification. In other cases, SWP and diversification actions may take longer due to the need to collect additional data to inform planning. For example, in the Upper Tana basin of Kenya, water planners used SWAT to model various SWP options to reduce sediment contamination in multiple reservoirs; however, researchers were unable to model both historical and projected climate and land use uncertainties due to lack of data, and a year-long study was required to collect sediment data for calibration (Hunink et al. 2013).

In the worst-case scenario, the lack of data to inform planning can introduce new threats to water quality and quantity. For example, when cities diversify their water supply sources through a transition from an exclusive reliance on surface water supplies to integration of groundwater sources, there are often no existing data to ensure damage such as over-abstraction is not occurring (Matthews et al. 2019; Rees 2006). This is especially important when new water sources may pose unknown risks to water users, as happened in Flint, Michigan in 2014, where changes in the municipal water source led to a drastic increase in lead contamination of tap water, particularly in vulnerable communities, leading to adverse health impacts (Jahng and Lee 2018).

To address this challenge, researchers and CWAs have worked to **adapt frameworks** to fit the needs of their cases. For example, the Piracicaba, Capivari, and Jundiaí (PCJ) River Basin Agency that manages the main source water supply for São Paulo has begun incorporating new climate and streamflow data from the recent water crises to update the assumptions for day-to-day decision-making (KI São Paulo 2022). This is done using three, seven, and ten-day forecasts based on recently updated historical datasets. With the newest data from the most recent water crises, this information is closer to what the basins are currently facing. Although using only historical data limits the ability of agencies to predict or anticipate uncertainties that fall outside of historical bounds, it is clear that agencies are trying to incorporate new realities into decision-making.

Support from external institutions, including academic, non-profits, or donors, to collect and manage data can help CWAs to address data availability issues to inform future modeling and improve decision-making, as in the case of the Upper Tana basin SWAT analysis (Hunink et al. 2013). Research institutes, non-profit organizations, and universities have explored new methods to simulate future land use changes from reforestation or expanding urban areas and project the effects of climate change on water supply. For example, in Brazil, the Extrema Water Producer program, a source water protection program spearheaded in 2005 by The Nature Conservancy (TNC) and the municipality of Extrema, has been successful through support from a national water policy, a strong commitment from the municipality, and a network of experts in universities and civil society that provided monitoring and technical capacities for use in planning and implementation (Richards et al. 2015). With the backing of results from studies modeling the potential benefits of the Extrema Water Producer Program, program proponents have been able to secure support from municipal officials (Ozment et al. 2018). The PCJ Water Producer Programs in Joanópolis and Nazaré Paulista have had similar success, with the National

Box 4. Challenges to Success: Measurement of Nature-based Solutions in Manila, Philippines

In the Greater Manila area, water service providers have created and begun to implement water safety plans (WSPs), which include nature-based watershed management actions. However, although WSPs have been implemented by utilities affecting various source water basins and there has been progress in collaboration between public and private entities, providers have not been able to accurately measure water supply improvements from these nature-based solutions (Ertel et al. 2019).

Water Agency (ANA), TNC, and other partners also providing equipment purchase, installation, and maintenance of monitoring programs to understand the long-term effects of the restoration projects (Taffarello et al. 2017). However, academic research has shown that these types of monitoring programs are very few and only recently implemented, limiting the understanding of how much these types of programs actually contribute to improvements in water supply quantity and quality (Taffarello et al. 2017).

In addition to evaluating diverse water sources over time, monitoring the impact of SWP or diversification measures remains a challenge in low-resource settings without external or national support (see Box 6). This is critical for tracking potential unintended negative outcomes (such as groundwater depletion or water quality concerns), as well as to generate evidence to inform future plans and investments. In some cases, **citizen monitoring** or other informal monitoring processes can be used to fill this gap. For instance, while the Flint Water Study revealed weaknesses in the municipal monitoring program that did not protect its users from contaminated water, it also underscored the importance of maintaining robust academic-, community-, and federal-level monitoring and data management programs that were able to step in when the city failed. However, these types of programs rely on existing community involvement and may be less effective in cities that do not have a strong involvement of community actors.

Attending to chronic water service delivery challenges often takes precedence until a crisis occurs

Many CWAs in LMICs are plagued by chronic issues of poor source water quality and quantity that can lead to apathy or even acceptance among both CWAs and users (Grönwall and Oduro-Kwarteng 2017; GWP and UNICEF 2022; Padowski and Gorelick 2014; Sorensen 2017; Zambia Water Partnership and Water Witness International n.d.), and result in limited attention to the need for long-term planning for SWP and diversification. Across multiple cities there was a confirmation of the need to transition "from reactive to pro-active planning" that has been seen in other studies (Alaerts and Kaspersma 2022). However, in practice, many successful implementations of SWP and diversification have occurred during crises arising from threats, such as severe droughts, driven by climate change and population growth. In other words, an acute water quality or quantity event can provide impetus for better planning and attention to larger uncertainty considerations in planning overall (Box 7).

Box 5. Proactive Planning Following a Water Crisis in São Paulo

In São Paulo during the 2014-2015 drought, permitting restrictions were dropped, leading to an increase in well drilling in recent years by private users (Empinotti et al. 2019). This prompted studies into the status and sustainability of aquifers in the region; for example, numerical groundwater modeling commissioned by the Alto Tietê Watershed Agency Foundation (FABHAT) and State Water Resources Fund (FEHIDRO) found that the Baquirivu-Guaçu river basin aquifer can support a number of future increases in groundwater exploitation with proper monitoring and management (CTGeo and Labgeo 2017). At the same time, state actors worked quickly to fast-track infrastructure solutions to both improve the flexibility of existing surface water storage and secure sources from farther away that had been politically unviable prior to the crisis (Braga and Kelman 2020).

In Manila, while the decision-makers in charge of Manila's water supply publicly advocate for diversification, their large infrastructure plan follows the pattern of past investments. Since 2011, Metropolitan Waterworks and Sewerage System (MWSS) has been trying to construct the 600 million-liters-a-day (MLD) Kaliwa Dam, a large project similar to the Angat Dam. However, as a result of the decade-long delay in constructing this project due to social and environmental concerns, demand had to be met during the 2019 water crisis by developing an array of previously overlooked sources and technologies, including the use of modular treatment plants, which take advantage of smaller, localized water sources, like nearby rivers and streams (Cal 2022; Maynilad Water Services Inc. 2021).

Concerned civil society groups, academics, and technicians were able to **leverage public attention during and after crises** to push forward planning agendas that were previously considered fringe or unnecessary. However, relying on reactive planning is dangerous since it can result in loss of life, risks to human health and ecosystems, and economic damage. In Lusaka, a cholera outbreak led to emergency implementation of source water testing, increases in chlorine in distribution systems, and installation of alternative water sources in hardest-hit communities, but it also resulted in numerous deaths, and resurgence of cholera cases occurred as emergency planning systems were abandoned soon after the first outbreak (Sinyange et al. 2018). Thus, while these events can serve as leverage to raising awareness, they should not be considered a central strategy for building support for planning frameworks.

Lack of practice and resources to support participatory planning and modeling

Incorporating diverse stakeholder views into planning is often a challenge for LMICs, and studies have found that participatory planning processes that lacked formal mechanisms for feedback and capacity-building components often led to project failure from stakeholder protests (Halbe et al. 2018, 2020). For example, in South-West Guwahati, India, failed water supply projects were found to have poor public involvement, particularly during the initial input and assessment phase (Das, Laishram, and Jawed 2019). Yet, stakeholder engagement can be resource intensive and time-consuming, and literature on the use of participatory methods within the WRM sector note the difficulty in gaining uptake among CWAs, and the exclusion of marginalized populations, among other challenges (Halbe, Pahl-Wostl, and Adamowski 2018; Halbe, Holtz, and Ruutu 2020; Roque et al. 2022; Serrat-Capdevila, Valdes, and Gupta 2011).

Multiple barriers constrain the widespread application of participatory methods for planning in LMICs, including the fact that stakeholder engagement is time-consuming and expensive, while the benefits are not well understood by many decision-makers. In addition, the water agencies that typically lead planning processes for SWP and diversification are generally staffed by technical experts who rely on decision support systems that were developed for specific technical purposes, such as engineering designs (Halbe, Pahl-Wostl, and Adamowski 2018). Participatory modeling processes need to be context-specific to adapt to physical, environmental, socio-economic, and institutional circumstances. Because CWAs typically do not have the resources to invest in developing appropriate participatory modeling methods, these efforts are often led by modeling experts as part of research projects constrained to looking at short- and mid-term interventions (Voinov and Bousquet 2010).

In planning for inclusive stakeholder engagement, CWAs must consider the challenges in participation and empowerment of vulnerable populations, capacity building, and potential techniques to promote inclusion, such as communication and facilitation of project information to disadvantaged communities (Calaguas and Francis 2004; Tripathi and Thapa 2019). There is an array of **decision support and analysis tools that enable facilitators to guide stakeholders** through decision-making processes (Langsdale and Cardwell 2022). Best practices highlight the importance of balancing qualitative (e.g., interviews, surveys, and facilitated workshops) and quantitative (e.g., GISs, Bayesian models, cost/benefit analysis, and integrated modeling) methods, as well as early and continuous participation of a diverse set of stakeholders (Langsdale et al. 2013; Voinov et al. 2018). However, there are currently very few examples of participatory modeling used for directly supporting decision-making, and most rely on minimal participation and only in the initial or final stages of modeling (Hare 2011).

Additionally, **accessible visualization methods and explanations of modeling** results targeted to the needs and skills of specific populations are imperative for enabling effective participation. In the Atitlán Basin, Guatemala, for example, multi-level storylines for participatory modeling were used to build a model based on the verbal input of marginalized communities, specifically the Mayan communities of Kaqchikel, Tz'utujil, and K'iche' (Bou Nassar et al. 2021). In this participatory approach, semi-structured one-on-one interviews in native languages with community members were used along with focus group discussion inputs to construct the macro-, meso-, and micro-level storylines, which shaped the model constructed. This focus on verbal input collection allowed for the participation of less literate individuals and ensured that lived experience was at the center of model construction. This approach built trust with the communities and led to the development of a model that represented the realities local groups face, which allows for more robust planning.

3.1.3 CONCLUSIONS ON PLANNING FOR RESILIENT URBAN WATER SUPPLY

Cities and utilities have used various planning frameworks for organizing and evaluating potential SWP and diversification projects to adapt to climate change and other vulnerabilities, but these can only be used effectively when underpinned by data tools, modeling and analysis capabilities, and effective stakeholder engagement. In LMICs, scenario analysis is the de facto planning framework for evaluating SWP and water supply diversification; however, it generally does not provide a robust consideration of the true range of uncertainties or stakeholder perspectives. CRIDA and RDS, having been developed specifically for implementation in LMIC settings, are well suited to consider various uncertainties while also accounting for gender and social inclusion. DAPP is typically inaccessible to users in LMICs as its techniques usually require experience with complex optimization methods and high computational capacity. However, these planning frameworks are often not well adapted to the technical capacity, governance systems, and data availability of cities within LMICs. There are a wide range of analysis and modeling tools that have been developed for assessing city- and watershed-level conditions and predicting changes because of interventions, but in many cases, use of these tools remains largely academic or outside of the realm of CWA analyses. Investment in data monitoring and management systems that can be sustainably managed by local institutions is critical to enabling cities and utilities to effectively plan.

In many cases, CWAs are dealing with chronic challenges and are unable to prioritize long-term planning until a crisis occurs. As a result of these challenges, many SWP and diversification planning exercises in LMICs have only been undertaken as part of "projectized" or donor-driven activities with significant external support, often without promote self-sustaining local technical capacity to support modeling efforts within CWAs so that when these projects conclude, their progress cannot be carried forward by local staff. Others have been foreign research projects, supported by local stakeholder participation, but not designed to create sustainable capacity. Even when capacity building is provided, it is often short-term or too generalized to incorporate the complexities of SWP and diversification scenarios.

3.2 NEGOTIATION FOR RESILIENT URBAN WATER SUPPLY SECURITY

CWAs must be able to effectively negotiate for the ability to implement SWP and diversification measures across a wide range of stakeholders. The second research question examines promising negotiation methods that can promote the successful implementation of SWP and diversification measures within different institutional mechanisms in LMIC contexts:

How can water utilities and cities negotiate within multiscale regulatory and institutional frameworks to better advocate for and implement SWP and diversification measures to ensure the resilience of urban water supply?

3.2.1 SUCCESSFUL NEGOTIATION AND INSTITUTIONAL MECHANISMS

The governance of a city's water supply is embedded within larger institutional mechanisms, where CWAs typically have either shared control or no control over the governance of the watersheds or aquifers within which they operate. Most countries manage water at watershed to river basin scale, and cities need to negotiate with those institutions to obtain water. There are exceptions of course, particularly with capital cities. Water resource constraints are affected by national policies and water allocation decisions made at various levels of government and can have an impact on urban water supply. Cities' abilities to successfully advocate for their water needs depend on a myriad of factors, including the size of the city, the legal-regulatory-institutional setting, and their ability to negotiate across a multiscale and complex institutional environment.

Institutional Mechanisms

Power to allocate water resources is intrinsically related to the power to incentivize, or successfully negotiate for, investment in SWP and diversification. Those with the power to allocate water rights[9] often also have influence in the water projects that are prioritized and receive financing. The institutional mechanisms for water allocation within which CWAs operate have a significant impact on the negotiation methods used by CWAs. The literature breaks down institutional mechanisms for water allocation into three approaches: public allocation, user-based allocation, and market allocation (see Table 5) (Meinzen-Dick and Mendoza 1996).

Table 5. Definitions of institutional mechanisms for water allocation

Allocation Mechanism	Definition
Public allocation	Allocation decisions made by the government.
User-based allocation	Allocation decisions controlled by users with a direct stake in the use of the water, often operating within the confines of a pre-defined water right.
Market allocation	Allocation decisions of tradable water rights made by rights holders/water users.

Meinzen-Dick and Mendoza 1996

When the state plays a dominant role in water allocation decision-making, the institutional mechanism of **public allocation** of water resources occurs. "Top-down" refers to objectives and instruments set by bureaucracies through formal legislative and regulatory processes. These tend to be overseen by higher, governmental organizational levels. This top-down approach to water allocation has historically been the most widespread institutional mechanism for water allocation globally, with countries such as Jordan still heavily relying on this mechanism (see Box 8).

[9] The terms "water rights" and "water tenure" are sometimes used interchangeably; however, USAID's *Introduction to Water Tenure* notes that water tenure focuses on water users and extends further to include the uses of water that may be customary, informal, or illegal (USAID 2023). In this review, we focused primarily on the methods for allocating formal water rights, although customary or informal rights will also influence the success of negotiations.

Box 6. Public Allocation of Water in Amman, Jordan

In Jordan, the national government oversees all water allocation decisions. The Ministry of Water and Irrigation Law establishes the Ministry of Water and Irrigation (MWI), who plays the central role in water governance and management. MWI is responsible for monitoring, planning and management, and strategy and policy development, including monitoring the use of water resources. A Council of Ministers determines and sets the tariffs for water supply that are used by Miyahuna, Amman's water utility.

The Water Authority law establishes that all water resources (surface water and groundwater) are owned entirely by the state and cannot be used or transferred outside the limits allowed by the Water Authority Law. The Water Authority of Jordan, which sits within the MWI, is responsible for regulation, surveillance and conservation of water resources, and determining priorities for use.

In recent decades, the recognition of the importance of stakeholder engagement and gender equity and social inclusion considerations in water resource decision-making has resulted in the integration of more bottom-up, community-focused initiatives—thus the **user-based allocation** approach has grown in popularity. This approach grants collective action institutions the authority to make water allocation decisions and encompasses voluntary, informal catchment partnerships. As the use of bottom-up approaches to urban water supply issues have spread, they have advanced in their influence and grown from small-scale initiatives at the local level to approaches driven at multiple scales (local, regional, etc.). At times, these approaches can appear to challenge top-down policies and decision-making structures (Cook et al. 2013).

A third institutional mechanism for water allocation is **market allocation**—i.e., contexts in which water markets operate, either formally or informally. Market allocation systems aim to structure economic incentives for water users (whether irrigation, industrial, or municipal users) to consider the full opportunity cost of water when making water use decisions. In California, farmers in the Central Valley and stakeholders across much of the state have actively traded surface water since the early 1990s. This has allowed water users who have rights to more ample water supplies and lower-value uses to sell or lease water to stakeholders with more limited water supplies but higher-value uses such as in agriculture, urban centers, and the environment (Ayres et al. 2021).

The institutional mechanisms in which CWAs operate can include combinations of allocation approaches. Examples of institutional mechanisms that combine tenets from both public and user-based allocation mechanisms include Integrated Catchment Management (ICM), flexible polycentric water governance structures. These types of hybrid mechanisms are now employed in the United States, United Kingdom, Canada, France, and New Zealand (Cook et al. 2012; Rouillard and Spray 2017).

Negotiation Methods for Advocating for Investment in SWP and Diversification

In LMIC contexts, cities, especially capital cities or those with political clout, often have the most negotiating power, as they are typically the industrial and commercial centers within countries. This gives them greater priority in negotiations over water allocation, making negotiating for investments in SWP and diversification, regardless of the institutional mechanisms, much easier (Molle and Berkoff 2009). From that position of power, cities can create or exacerbate inequities in water allocation. Even so, LMIC cities still face significant challenges to negotiating for SWP and diversification, as discussed in the following section.

Within public, user-based, and market allocation institutional mechanisms, CWAs can utilize specific negotiation methods to increase the successful advocacy for and implementation of SWP and diversification measures. This study highlighted (1) incentivization, (2) trusted intermediaries, and (3) public buy-in as three negotiation methods that promote cities' ability to advocate for their water needs.

However, it is important to highlight that the baseline influence a city has in negotiations within broader, multiscale institutional structures varies between cities, and thus the same negotiation method employed in two different cities rarely has the same effect.

Incentivization

The use of incentives is a powerful method to increase positive outcomes for urban water security (Qureshi et al. 2012; Molle and Berkoff 2009) and has long been used to motivate water users to more efficiently utilize water resources. Although this negotiation method is applicable across all institutional mechanisms, it is most frequently observed in market-based allocation. Cities have used financial compensation to incentivize water users to use their water resources more efficiently or to provide water transfers, an important diversification measure. For example, cities in Chile can now purchase water directly from farmers, or in some cases even purchase a portion of farmers' water rights. For SWP, incentives can also be financed by cities via water funds and payment for ecosystem services (PES) (see Section 3.4.1 for more details).

In addition to financial compensation, incentivization can also take the form of legally binding commitments made by cities to decrease their water demand in return for access to additional water supply. Water transfer agreements that include a formal stipulation that a city must make an effort to reduce its water losses or its consumption as a condition of the agreement helps to strengthen the likelihood of successful negotiation outcomes for cities, as these stipulations help appease the other negotiating parties (Molle and Berkoff 2009). Examples of this include the agreement El Paso made when it obtained water from the Rio Grande in the 1990s on the condition that the city reduce per capita consumption, recycle sewage water and eliminate leakage (Earl and Czerniak 1996). Similarly, in the case of Delhi and the Upper Ganga irrigation scheme, the agreement included the lining of irrigation canals paid for by the cities (Molle and Berkoff 2009).

Though incentivization is inherently housed within a market allocation mechanism, market allocation often takes place at the smaller, local level within broader institutional mechanisms of public or user-based allocation at regional and/or national scales. As such, incentivization can be an important part of negotiation strategies across all three water allocation mechanisms.

Trusted intermediaries

Across water allocation mechanisms, excluding pure public allocation, when negotiating across scales and stakeholder groups, the use of **trusted intermediaries** can help ensure productive discussion and a space where all included stakeholders can share their needs (Rouillard and Spray 2017).

In some cases, intermediaries are independent and have no vested interest in the outcome of a negotiation; in others, intermediaries can consist of representatives from each affected stakeholder group—thus ensuring equitable representation in negotiations (see Box 9). In both options, it is imperative that the intermediary ensure the decision-making process is transparent, including a high level of information sharing and opportunities for input that are well-publicized (Kingsford et al. 2017; Pahl-Wostl, Palmer, and Richards 2013).

Box 7. Motueka ICM Group: Water Augmentation Committee (Waimea, New Zealand)

The Waimea River catchment lies west of Richmond and Nelson City, New Zealand, and includes within it a diverse range of horticulture and crops. The river is also a valuable source of recreational activities for communities within the catchment. Approximately 3,700 hectares (ha) of the plains are irrigated, mostly from shallow groundwater, to support farming activities; however, this groundwater pumping occasionally causes the river to run dry, falling below environmental flow requirements. This has led to water insecurity for irrigation and water use restrictions during seven of the last nine years.

In 2003, parties dependent on the river sought a collective solution and created **a committee representing all stakeholders**. The group has negotiated potential solutions, including: (1) potential construction of dam sites and out-of-catchment water augmentation options; (2) assessment of environmental, cultural, and out-of-stream flow and water quality requirements; and (3) debates over costing and governance options. All negotiations were transparently communicated to stakeholder group members, and their input continued to be incorporated in discussions via their representatives on the negotiation committee. A partnership consisting of local governments, irrigators, and environmental interests has provided funds for these activities. It is likely a dam in an upper tributary to augment natural river flows during dry periods will be constructed. This group has become a leading example of collaboration in New Zealand between originally conflicting parties and the power of an intermediary to promote successful negotiation (Cook et al. 2013).

The use of trusted intermediaries for negotiation can help to promote shared decision-making among stakeholders—a key component specifically within collaborative governance approaches to water management (Susskind 2013). Shared decision-making processes can be decentralized; however, mechanisms for coordinating decisions across all levels of government, including local and higher-level authorities, are essential for success. This often coincides with a need for strong societal and government leadership—a reason why many intermediaries are a result of institutional restructuring, such as in post-socialist states in the EU (Kingsford et al. 2017; Moss et al. 2009; Pahl-Wostl, Palmer, and Richards 2013). In the Philippines, the National Economic and Development Authority (NEDA) is mandated to formulate national development plans, sector policies and strategies, and review implementation, which often places them in the role of a trusted intermediary. NEDA led the complex process of facilitating the collaboration of hundreds of water-related stakeholders across the country, and 30 water-related governmental institutions (including their departments and various offices), and gathering their inputs to inform the development of the Philippine Water Supply and Sanitation Master Plan (2019–2030) (NEDA 2021).

Public buy-in

Where stakeholders feel excluded from decision-making, **public buy-in** can promote successful negotiation. Public buy-in is most prominently observed in user-based allocation and mechanisms that merge user-based and public allocation. This is because user-based allocation inherently engages a wider set of stakeholders and voices and thus enables the development of public buy-in more readily than public allocation mechanisms. In public allocation, public buy-in is typically not an influential driver for SWP and diversification project implementation decisions, as these decisions are made largely unilaterally by national government. In purely public allocation mechanisms, public buy-in may be dismissed, or in some cases even have negative consequences for those who mobilize to call for certain governmental action—in a dictatorship, for example.

CWAs have recognized the importance of mobilizing the public to support and buy into SWP and diversification projects in cities. To illustrate, Singapore has diversified its water sources, called the "Four National Taps" which consist of: (1) imported water from Johor, Malaysia; (2) local catchment water; (3) NEWater; and (4) desalinated water, to achieve a sustainable and robust water supply to meet increasing water demand. The third tap, NEWater, is highly purified water produced from treated used water for direct non-potable use and indirect potable use using advanced membrane technology. Singapore's PUB—the national water agency responsible for city water supply—knew that it would be a great challenge to introduce NEWater, as historically, indirect potable use had been among the most difficult water initiatives for implementation. PUB embarked on a public communication plan that not only focused on media and the international experts' positive technical views on NEWater, but also on frequent involvement of political and community leaders to promote NEWater and address the sentiments of Singaporeans. This was effective in obtaining the public's buy-in into NEWater, which PUB then leveraged to garner additional governmental support and investments to implement the introduction of NEWater.

The case of Day Zero in Cape Town also provides a strong example of the power of public buy-in to successfully implement SWP and diversification measures. During the water crisis, the City of Cape Town (tasked with water supply oversight and provision) implemented several demand management and reduction strategies that have since remained. These included public education and free resources to help individuals decrease their water use without impacting livelihoods or quality of life. Free educational materials as well as a sense of responsibility to protect water supply in the city led to successful reduction of demand and ultimately, coupled with eventual rainfall, an aversion of Day Zero. Since 2018, research has shown that the buy-in of the public to demand reduction has proven the most effective long-term solution to water supply security in Cape Town, as opposed to options such as desalination which are viable only as short-term solutions to date due to cost (Quandt et al. 2022). The support and public backing of demand management initiatives act as proof of the potential return on investment for these SWP and diversification projects to the national government, which promotes CWA negotiation power to request continued government investment in SWP and diversification projects.

Table 6 provides a summary of the negotiation methods that are most appropriate for the institutional mechanisms within which a CWA operates. In addition to this institutional context, the most appropriate negotiation method will depend on contextual factors such as the presence of intermediaries, power dynamics, and access to finance.

Table 6. Summary of negotiation methods for CWAs and the institutional mechanisms within which they operate

LEGEND	
(green)	Commonly used, effective
(yellow)	Less frequently used, can be effective

Negotiation Methods	Institutional Water Allocation Mechanisms			
	Public Allocation	User-based Allocation	Market Allocation	Hybrid Allocation
Incentivization				
Compensation to water users				
Legally binding commitments by cities				
Trusted intermediaries				
Independent third-party intermediary				
Representatives from each affected stakeholder group				
Public buy-in				
Buy-in of community members and institutions				

3.2.2 NEGOTIATION CHALLENGES AND ENABLING FACTORS FOR SUCCESS

These negotiation methods—incentivization, trusted intermediaries, and public buy-in—can be powerful tools to enable the successful implementation of SWP and diversification projects. There are, however, key challenges to the use of these methods in LMICs, including: (1) power dynamics that favor larger, often national institutional actors; (2) intersectoral conflict among stakeholders over water allocation; (3) transboundary conflict; and (4) policy fragmentation leading to unclear role delineation and limited capacity. These challenges can perpetuate the continued marginalization of vulnerable groups. To address these challenges to successful negotiation for SWP and diversification efforts, enabling factors used by LMIC cities can include: (1) participatory processes in decision-making, (2) institutionalized environmental regulations, (3) "soft-law" instruments, and (4) strong and charismatic leadership.

Power Dynamics

Water supply is typically allocated to those who have the most power rather than the most need. This perpetuates unequal power dynamics between decision-makers, which restricts water supply management flexibility, creativity, and suitability. Often, traditional top-down institutional mechanisms, politics, and power dynamics are barriers to holistic and flexible planning and decision-making approaches. For example, watershed protection, decentralized solutions, and demand management are often left off the table in favor of plans for expanding centralized conventional water supplies (e.g., new dams, desalination, new pipelines). This is especially true in the power dynamics between national or state interest groups and less-powerful interests—though power dynamics are also at play within CWAs. In Amman, for example, Miyahuna (the water utility) struggles for autonomy, trying to break from the government but having limited decision-making power as an institution of its own (Amman KI 2022). Staff at MWSS in Manila report that demand management is not the clear responsibility of one department within the agency and as such does not have a proponent within water supply decision-making—an illustration of the power dynamics within a CWA (KI Manila 2022b).

Power dynamics can influence the effectiveness of using incentivization as a negotiation mechanism for increased investment and implementation of SWP and diversification measures. Market power may emerge in these instances, further perpetuating power imbalances. Similarly, in environments of high-power concentration, the use of trusted intermediaries is rarer as stakeholder representation is not prioritized. Finally, in heavily top-down structures, or where one stakeholder has the majority decision-making power, public buy-in may simply be ineffective or too high risk. Public allocation mechanisms tend to experience the highest likelihood for power imbalances, though this can also be seen in market allocation if monopolies or monopsonies emerge.

The decentralization of power and decision-making around water resources management can improve negotiation for SWP and diversification. Increased local stakeholder involvement in decision-making processes can achieve more efficient local implementation of various strategies. Though decentralization processes are not realistic in all contexts, some LMICs have recognized this as an enabler to more successful negotiations and have begun efforts to reshape institutional water management structures, as with the case in Addis (see Box 10). While decentralization of decision-making can address unequal power dynamics and thus promote the use of effective negotiation methods, the implementation of this enabler is not without challenges. Lack of inter-municipal collaboration and insufficient central government financial support when transitioning to institutional structures that include multiscale governance can hinder progress (Corfee-Morlot et al. 2009). LMICs specifically may struggle more with successfully implementing these institutional transitions as the capacity and financial resources to

Box 8. Decentralization of Water Resources Management in Addis Ababa, Ethiopia

Ethiopia has enacted new laws and policies that address water resource issues and realities. Historically, the Federal Ministry of Water Resources was granted most of the power and responsibility for water resources management and allocation. However, the government recently adopted the river basin as a planning unit for the development and management of the water resources. This decision is in line with the Ethiopian Water Resources Management Policy and has resulted in Regional States taking ownership of a large portion of the federal government's water responsibilities and power. Most of the major powers and responsibilities of the Federal Ministry of Water Resources should now be delegated to River Basin Organizations (RBOs). These are set to be established in phases and Regional States are expected to play a major role in these RBOs' decision-making (Tamrat 2008). Steps such as this are largely motivated by Ethiopia's desire to ensure the local government is the prime driver of legal action and development in their respective communities.

implement such transitions may be limited. Though central government may have good intentions when outlining institutional transitions, the actual coordination to ensure successful transitions can a challenge.

Another enabler to effective negotiation that can address power dynamics is the use of participatory approaches to decision-making (Azharul Haq 2006; Hamel and Tan 2022; Hassenforder et al. 2020; Howe and Mitchell 2011; Mohammadkhani et al. 2020). This is achieved through promotion of long-term collaboration and participation among stakeholders, as well as the increase of buy-in to SWP and diversification plans (Vicuña et al. 2018). One of the most effective strategies to ensure stakeholder engagement via participatory processes, and thus ensure proper implementation of SWP and diversification projects, tends to come from multi-disciplinary efforts. In São Paulo, for example, the Extrema Water Producer program, a project promoting rural landowners to adopt water and soil conservation practices in south-eastern Brazil, was successful through support from a network of experts in universities and civil society that provided technical capacities and monitoring and evaluation for its project planning and implementation, which helped the municipality justify the program to decision makers and participants (Richards et al. 2015).

Sectoral Conflict

The inability of decision-makers to resolve sectoral conflict stemming from differing perspectives on water use priorities hinders productive and effective negotiation and disincentivizes investment in SWP and diversification measures. When sectors have vested interest in SWP and diversification projects, they are more likely to invest time and resources to ensure project success—this includes cooperation in negotiations. Unfortunately, in many LMIC cities, government agencies overseeing certain sectors operate in siloes, lacking the coordination necessary to align water priorities and allocations, which perpetuates sectoral and user group conflicts.

For example, agriculture is the largest sector competing for water resources with the residential supply sector in Jordan, using approximately 50% of Jordan's groundwater resources. In Amman, plagued by high water scarcity, the trade-off between agricultural productivity and residential access to water is significant, pointing to the importance of alignment between national priorities for the allocation of water and city-level responsibilities to provide water for residential and other users (Fanack Water 2022). Agriculture presents the main competing water demand for residential drinking water in Cape Town as well; however, the city has regulations to ensure all sectors receive their water needs during non-drought years, as illustrated in Box 11 (Rodina 2019). In Manila, upstream rural farmers suffer at the expense of downstream urban residents during droughts, as legal prioritization is given to the city's water supply over that of the marginal conditional water rights for the irrigation system located nearby the Angat dam, where Manila sources most of its water supply. This policy does not always compensate farmers for their lost crops, nor does it take into consideration the comparative economic impact of water reductions on poor rural farmers versus wealthier urban consumers (see Tabios and David 2004 for opportunity cost analysis).

The sectoral conflict between hydroelectric interests and water supply interests in São Paulo has led to various lawsuits from the energy sector against the water utility during times of drought when the hydroelectric plants were unable to operate due to low reservoir levels (SEC 2018). Similarly, energy companies have led the fight against the interconnection of the Paraiba do Sul basin with the Cantareira system to supply more water to São Paulo at the expense of energy production in the source basin in dry years (Kelman 2015). This is a direct example of the energy sector's ability to negate CWA attempts to diversify water supply via system interconnection.

Box 9. Participatory Processes Enable Successful Sectoral Negotiation in Cape Town

Institutional coordination during the Day Zero water crisis in Cape Town in 2018 offers a success story in the realm of cooperation and collaboration between stakeholders. During the crisis, the South African government undertook a large array of initiatives to align water priorities and allocation across all levels of government—initiatives that have continued since the crisis, such as coordination among sectors on annual allocation amounts and policies for sectoral prioritization for water allocation in times of stress or crisis (OECD 2022). Cape Town city regulations ensure all sectors receive their water needs during non-drought years. In cases of drought, demand-side cuts in water access have been the main mechanism used by the city to conserve water, ensuring sectoral conflict is avoided (Rodina 2019). The participatory process used to negotiate these regulations ensures stakeholders are included and therefore buy in to strategies. This buy-in enables successful strategy implementation and execution.

Specific participatory processes that have been used in Cape Town and surrounding areas include the establishment of catchment management agencies to localize water allocation decisions; use of participatory developmental project cycle management to train participants on project development for poverty and inequity alleviation within the water sector; and the "Champions Programme," which aimed to empower members of surrounding Cape Town communities to act as links between their communities and decision-making forums on water allocation (Schreiner et al. 2004).

Sectoral conflict impacts all three negotiation methods described above. Incentivization of water users is less effective as sectors cannot coordinate on incentivization structures and monitoring, as illustrated by the case study of Manila above. Trusted intermediaries are more challenging to agree upon and utilize if there is inherent distrust among sectors. Public buy-in may result in some internal action within each sector; however, without coordination, sectors are likely to implement siloed approaches to address challenges, which often results in ineffective solutions.

The use of **institutionalized environmental regulations** can provide motivation to sectoral users to improve water usage and contribute to the protection or development of water sources. In São Paulo, the state environmental regulator implemented a new pollution permit scheme to replace perpetual wastewater discharge permits for companies with renewable permits that required companies to continuously update and improve their water use practices to meet new limits as the permits were renewed (CETESB 2005). Reductions in wastewater discharge were achieved mainly through reductions in total water use and increases in on-site water recycling, leading to significant reductions in overall water demand among industrial users (Ribeiro and Kruglianskas 2013). A similar step was taken in Quito, where minimum environmental flow requirements were recently incorporated into water regulation, along with the inclusion of the rights of nature in Ecuador's constitution (Ecuador 2021). Though these flow requirements have yet to be implemented, they are likely to impact water supply to the city and thus perpetuate a shift toward new water supply sources.

Box 10. Large-scale Institutional Collaboration in Lusaka to Promote Urban Water Security

In 2016, the Lusaka Water Security Initiative (LuWSI) began taking steps toward better water security by creating a collaborative platform that facilitates knowledge production, sharing of best practices, and development of pilot projects among stakeholders. The project brings together 33 partners from the public sector, private sector, academia, NGOs, international donors, and civil society actors to facilitate dialogue, coordination, and collaboration on water security projects within an urban and peri-urban context (LuWSI 2022a). Due to the project's success, some partners have expressed interest in transforming the initiative into a legally binding institution that would codify the actions of public and private actors for collaboration on water security. This could allow for more project coordination on a larger scale, so that more people can benefit from these projects (KI Lusaka 2022).

Environmental regulations have in some cases led to **multidisciplinary collaboration** between institutions, academia, industries, civil society, nongovernmental organizations (NGOs), and development agencies, as they may have individual motivations toward similar goals and can thus enter into partnerships to pool resources and absorb costs. These collaborative networks can translate risks into collective action toward effective projects, policies, and plans. For successful policies to come about, there needs to be a shift in how policymakers think about water security. It cannot just be seen as a "technical" problem that can be solved by engineers; rather it needs to be put in the context of participatory decision-making at multiple scales and across sectors, especially when faced with continued urbanization, development, and globalization. Since these processes are ongoing, they require continuous attention from different stakeholders, which inherently ensures more diversity of voices at the table (see Box 12).

Transboundary Conflict

Many LMIC cities are situated in transboundary river basins, which creates institutional uncertainties that further challenge successful negotiation for city water supply in the context of diversification and SWP efforts and put existing and future water supplies at risk. Historically, there are few examples of successful transboundary river basin agreements focused on urban water supply, mainly because, historically, water requirements for irrigation and hydropower are greater and likely to have a notable impact on basin flows. However, given the trends outlined above related to climate change, growing water scarcity, and growing urban water demands, city water supply is likely to become increasingly relevant at a transboundary level. At present, uncertainties driven by reliance on transboundary river flows to satisfy urban water supply can be only partially mitigated by diversification measures as states do not have sole rights to transboundary waters, nor can states institute SWP measures as they cannot dictate the actions of other states unless a legally binding agreement is reached via negotiation. Lack of cooperation in such negotiations is often perpetuated by longstanding political conflicts, as is the case in Central Asia with the significant loss of the Aral Sea, or the years-long conflict in Syria.

Incentivization in transboundary contexts is complicated by the various governance structures at play around water bodies which challenge the implementation of an effective, international incentivization structure. It can be a challenge to agree on trusted intermediaries, as the vast field of stakeholders involved in transboundary negotiations often have individual agendas and, in some situations, historic distrust of one another. Finally, public buy-in, unless large scale, is often not effective in promoting negotiation, as mobilization in one country does not necessarily result in buy-in in another country. For all three negotiation methods, the added complexity of transboundary environments exacerbates existing water supply pressures.

Amman, for example, greatly relies on transboundary water sources, such as the Jordan River and Yarmouk River that provide most of the city's supply. Unfortunately, other nations have not always held to their agreements with Jordan regarding water allocation from shared sources. For example, a large portion of the Jordan River's flow is diverted by Israel upstream of Amman, and Syria has constructed more than 20 dams upstream of Jordan's border (Müller et al. 2016). Due to the transboundary nature of these water sources, the institutional mechanisms within which they are situated are highly complex, and the ability of cities to negotiate successfully is affected by a multitude of factors outside cities' control. Similarly, in São Paulo, a number of source water basins are located partially or completely in other states, leading to the inclusion of federal agencies to manage water resources and creating difficulties in aligning long-term planning goals with other states' sectoral interests (Johnsson and Kemper 2005; KI Quito 2022b).

An enabler to successful transboundary negotiations is the use of **"soft-law" instruments**, non-binding documents, which outline standards states are encouraged to follow in such negotiations, specifically as they pertain to aquifer negotiations. Such aquifer-specific instruments are the United Nations (UN) "Draft articles on the law of transboundary aquifers" and the "Model Provisions on Transboundary Groundwaters" made under the umbrella of the 1992 UN Economic Commission for Europe Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Burchi 2018). In addition, the 1997 Convention on the Law of Non-Navigational Uses of International Watercourses addresses the use of all waters that cross international boundaries, including both surface and groundwater. Although none of these are legally binding, they include core rules within them on state behavior (rules of customary international water law), which are legally binding. These rules set standards for states to follow in negotiations to ensure a basic standard of fairness. Customary law often plays a significant role in transboundary water negotiations, as it shapes the norms and practices that govern water resource management between neighboring communities and countries.

Box 11. Successful Transboundary Cooperation in the Disi Aquifer

A transboundary success story at the city scale is the use of the Disi aquifer for the city of Amman, and the pumping agreement between Jordan and Saudi Arabia. The agreement enforces exclusion zones within the Disi aquifer, a key nonrenewable source of groundwater shared by Jordan and Saudi Arabia, which relies on a joint technical commission to enforce the agreement. It is the first agreement of this type between sovereign countries and has a promising potential to avoid conflicts or resolve potential transboundary groundwater disputes over comparable aquifer systems elsewhere (Müller et al. 2017).

The UN Draft Articles document was in large part informed by the knowledge-generation and mapping exercise of the world's international transboundary aquifers carried out under Internationally Shared Aquifer Resources Management (ISARM). This is a joint initiative of UNESCO-IHP, UN/FAO, and the International Association of Hydrogeologists. ISARM's work has highlighted the existence of aquifers under territories that stretch beyond international boundaries with neighboring States and has also crystallized the opportunities generated via cooperation between States. The Disi Aquifer Agreement (Box 13) was influenced in part by these soft-law instruments and the work of ISARM. This is an example of how trusted intermediaries (institutions such as ISARM) can play a critical role in motivating productive transboundary negotiation if situated within an enabling environment (Burchi 2018).

Policy Fragmentation

Every city faces a complex set of decision-making processes that are multi-scale, with multiple stakeholders and institutions. Given this complexity, there often is a lack of policy coherence that results in an absence of clear institutional responsibilities. This is a result of numerous factors, including evolving institutional mechanisms, fragmentation, and tension among levels and sectors of government, legal frameworks, and lack of inter-municipal cooperation and central government support. When institutional responsibilities are unclear, CWAs' ability to successfully negotiate for investments in SWP and diversification can decrease, as they are not always granted a position within water-related decision-making. This is because a CWA's role within an evolving institutional structure may change or certain responsibilities may be delegated elsewhere, calling into question the CWAs legitimacy in decision-making processes.

For example, CWAs may be responsible for water delivery, while river basin authorities have responsibility for water allocation across much larger geographies with competing interests, such as agriculture, mining, or hydropower. In many countries, what was once a system largely overseen by a central government with a hierarchical, top-down approach has now decentralized to allow municipalities and local governments to take on greater responsibility for water policy implementation (Ojha et al. 2020; Rijke et al. 2013; Romano and Akhmouch 2019). As cities face the imminent reality of climate change and changing demographics due to urbanization, institutional changes are expected to continue, which presents a challenge to CWAs' abilities to successfully negotiate, specifically in LMICs where clear leadership and financial resources are not always established (Corfee-Morlot et al. 2009; Romano and Akhmouch 2019).

Without a clear policy framework and enforcement, incentivization structures as a negotiation strategy have a greater risk of resulting in market power imbalances. Trusted intermediaries are also forced to deal with the added challenge of how to effectively support a negotiation when the roles of the negotiating parties are unclear. Lastly, public buy-in will continue to be ineffective if stakeholders cannot coordinate and implement responses.

In situations of policy fragmentation, **strong leadership,** especially charismatic or heavily involved leaders, can help cities outline more clear responsibilities—thus aiding in more productive negotiations and promoting SWP and diversification project success. Strong leadership was cited in several of the key informant interviews in Quito as one of the most important factors contributing to the successful establishment of new institutional structures and approaches for SWP and diversification (KI Quito 2022a). However, the changes championed by a strong leader must be institutionalized to survive changes in leadership. The Extrema Water Producer program in São Paulo has been successful through a strong commitment from leadership within the municipality who solicits support from a network of experts in universities and civil society that provide monitoring and technical capacities for use in planning and implementation (Richards et al. 2015). Richards et al. (2015) found that the municipal manager of the program was able to reduce transaction costs for participants in the program by providing connections between partners, ensuring the daily presence of staff in the sub-basins including active negotiation of customized restoration plans, supplying labor for restoration activities following enrollment, and securing an endorsement from rural associations. While this program has been very successful, it is reliant on the continued strong presence of a single municipal leader to champion its success.

3.2.3 CONCLUSIONS ON NEGOTIATION FOR RESILIENT URBAN WATER SUPPLY

The institutional mechanisms for water allocation—which define who has the power for allocating water resources—have a significant impact on how cities can most effectively negotiate for SWP and diversification measures. The literature breaks down institutional mechanisms for water allocation into three approaches: public allocation, user-based allocation, and market allocation, although hybrid mechanisms that combine two or more of these approaches are common. The research team identified three negotiation methods that have proven successful within these various institutional contexts from the literature: (1) incentivization, (2) trusted intermediaries, and (3) public buy-in.

Incentivization can either take the form of financial compensation for efficient water use or water transfers or can be commitments around reduction of demand and access to additional water supplies.

Incentivization is an inherent part of market-based allocation mechanisms but can also be used at local scales across public and user-based allocation mechanisms. The use of trusted intermediaries is most often observed where there is an element of user-based water allocation and can help promote shared decision-making among stakeholders and ensure equitable representation of all voices. While shared decision-making processes may be decentralized, mechanisms for coordinating decisions across all levels of government, including local and higher-level authorities, are essential for success. Gaining public buy-in is also most often used where there is user-based allocation, as such systems inherently engage a wider set of stakeholders and voices. Public buy-in has often been critical to gaining acceptance of demand management and wastewater reuse measures.

Though these negotiation approaches can be effective, they are contextual, with the ability of a city to successfully advocate for their water needs depending on a myriad of factors, including the size of the city and the legal-regulatory-institutional setting. Many cities within LMICs face key challenges, such as unequal power dynamics, conflict between sectors and transboundary water users, and policy fragmentation can create barriers to successful implementation of SWP and diversification measures.

3.3 FINANCE FOR SWP AND DIVERSIFICATION

Financing is a serious challenge to the realization of many SWP and diversification options, especially in LMICs. This section reviews financing models that have been applied successfully for protecting source water and achieving resilient water supplies through diversification, their pros and cons, and what factors contribute to or inhibit their success. The specific research question is:

What are viable and sustainable financing models for protecting source water and achieving resilient water supplies, and what are the factors that contribute to their success?

3.3.1 SUCCESSFUL FINANCING MODELS FOR SWP AND DIVERSIFICATION

The primary *sources of funds* used for SWP and diversification are generally the same as those for providing water, sanitation and hygiene services (USAID 2021b):

- *User fees (tariffs):* Fees paid by households, businesses, and public institutions to service providers, as well as household investment in self-supply solutions. Tariffs may include surcharges for specific purposes, such as stormwater management, watershed protection, or capital improvement programs.
- *Taxes (government)*: Funds originating from domestic taxes that are channeled to the sector by central, regional, and local governments.
- *Foreign assistance (external grants)*: Funds from international donors or charitable foundations.

These funding sources are channeled to projects through different *financing mechanisms*, which are divided into five categories: CWA annual operating budget, government programs, repayable finance, non-repayable finance, and innovative financing models (Table 7). This section describes how these financing mechanisms have been successfully used for SWP and diversification, particularly in LMIC settings, focusing specifically on two innovative financing models: water funds and government-subsidized PES projects. These innovative mechanisms can generate income from two additional sources: trust fund interest earnings and non-grant private sector investment in watershed protection.

Table 7. Sources of funds and financing mechanisms successfully used for source water protection and diversification

Financing Mechanism	Primary Source of Funds			
	User Fees/Tariffs	Taxes and Other Government Funds	Foreign Assistance	Other
CWA annual operating budget	Always	Sometimes		
Government programs		Always		
Loans, bonds, public-private partnerships (repayable finance)	Usually	Usually	Sometimes	
Grants (non-repayable finance)			Always	
Water funds, PES (innovative models)	Usually	Usually (for PES)	Rarely	Always (for water funds)

[1] *"Other" includes trust fund investment interest, which is an additional source of funds by design for all water funds, and non-grant private sector investments in watershed protection.*

Legend	
(dark green)	Always a source of funds
(light green)	Usually a source of funds
(yellow)	Sometimes used
(pink)	Rarely used
(grey)	Not applicable

The choice of appropriate financing models for SWP or diversification depends on the cost of the investment and its purpose. Two categories of projects that are particularly challenging to finance and have distinct sources of financing are: (1) large infrastructure projects, and (2) watershed protection projects. Large infrastructure projects are most often financed through repayable finance (loans, bonds, or PPPs) and sometimes through non-repayable grants. Watershed protection requires long-term sustained efforts and rarely yields immediate results. While regional or national government entities often contribute to reforestation programs, the most successful financing models for comprehensive watershed or aquifer management and protection have been through innovative financing mechanisms, such as PES schemes or water funds, both of which involve the structuring of an entity that is dedicated to that purpose.

The financing mechanisms most used for SWP and diversification across case study cities were grants from external sources, loans or bonds, CWA annual budgets, government programs, water funds, public private partnerships, and PES schemes (see Table 8). Effective SWP and diversification relies on a combination of various financing mechanisms and funding sources. The case study cities that have been most successful in financing projects have used a diversity of funding sources and models, often combining funds from various sources for a single project or program.

Table 8. Financing mechanisms used by case study cities for source water protection and diversification[10]

	Quito	Sao Paulo	Cape Town	Amman	Manila	Lusaka	Addis Ababa
Key contextual issues related to financing source water protection and diversification							
Income level	Upper middle	Upper middle	Upper middle	Upper middle	Lower middle	Lower middle	Low
Do annual revenues cover operation and maintenance costs?	Yes	Yes	Yes	125% without depreciation	Yes	108% without depreciation; 86% with depreciation	No
Non-revenue water estimate	27-31%[11]	27%[12]	20-30%[13]	37%	~30%[14]	47% [15]	35-40%[16]
Percent of urban population living in informal settlements	< 2%[17]	~ 20%[18]	18%[19]	n.d.	< 35%[20]	62%[21]	80%[22]
Financing models used for source water protection and diversification							
CWA annual operating budget	D, SWP	SWP	D, SWP		D, SWP		
PES		SWP					
Water Funds	SWP	SWP	SWP				
Regional or central government programs			D, SWP	D, SWP	D, SWP		D, SWP
Loans or bonds	D	D	D		D, SWP	D, SWP	SWP
Public-Private Partnerships				D	D, SWP		
Grants from external sources	SWP	SWP	SWP	D	SWP	D, SWP	D, SWP
Service coverage (one measure of results)							
Service coverage	98%	93%	88%	98%	94%	50-60%	76%

n.d. = no data, SWP = source water protection, D = diversification

10 See Appendix B for additional details.
11 Data corresponds to a range from 2010 to 2019 (SEI 2021)
12 Data corresponds to 2020 (Sabesp 2020a)
13 Data corresponds to 2018 (Water and Sanitation Department 2018)
14 Data corresponds to 2021 and is an average of Manila's two utilities: MWCI (15%) and MWSI (32-45%) (Manila Water Company Inc. 2022b; Maynilad Water Services Inc. 2022)
15 Data corresponds to 2021 (NWASCO 2021)
16 Data corresponds to 2021 (CWRA 2021)
17 Data corresponds to 2020 (EPMAPS 2021)
18 Data corresponds to 1990s (UN HABITAT and SEADE 2010)
19 Data corresponds to 2018 (Rodina 2019)
20 Data corresponds to 2020 (NEDA 2020)
21 Data corresponds to 2021 (Chiwele et al. 2022)
22 Data corresponds to 2011 (Yohannes and Elias 2017)

CWA annual operating budgets

CWA annual operating budgets have been successfully used to fund lower-cost SWP and diversification projects, such as public education, wellhead protection, leakage reduction, and green stormwater management. Although CWA annual operating budgets are a main funding source for SWP and diversification, priorities for annual operating budgets are (1) water/wastewater system operation and maintenance and (2) debt service. However, in a sample of 690 utilities in developing countries, only 15% were deemed financially viable, having achieved an operating ratio[23] of 120% or higher (Kolker et al. 2016). More recently, a 2021/2022 survey of 108 urban water providers found that only 41% had revenues that covered even 80% of operation and maintenance costs (World Health Organization [WHO] 2022). Six of the case study cities have sufficient annual revenues to cover operation and maintenance costs, excluding depreciation, so they are positive outliers in this sense. SWP and diversification measures financed with annual budgets available to water authorities found in the case studies include emergency measures, such as those implemented in Sao Paulo in response to an extreme drought in 2014, where new channels and coffer dams, used with floating pumps, helped the city to use what otherwise would have been dead storage in reservoirs.

Sometimes surcharges on tariffs or property taxes are established and dedicated to specific funds or uses, such as a capital improvement program surcharge. These may be placed in a dedicated fund for that purpose and managed by the CWA or a special oversight committee. In the case of Metro Manila, the regulator approved two private concessionaires to charge their customers an environmental fee of 20% of the water charge (basic charge plus transitory adjustment), which was used for wastewater management and treatment (Manila Water Company Inc. 2020). Effectively, this percentage of the water tariff is being used to create a financial incentive for a revenue neutral service by distributing the cost of septage management (i.e., CAPEX, operation and maintenance cost, and other financial costs) across the customer base, whether they are connected to the sewage system or use desludging services, because the whole community is benefitting from safer wastewater management. Similarly, these type of collective action fees on water tariffs can be used for watershed protection. One of the most notable examples of this is in Peru, where $112 million has been allocated using a percentage of the revenues from water tariffs to fund NBS investments by 37 (as of August 2020) of the country's water utilities (Coxon, Gammie, and Cassin 2021).

Government programs

The UN-Water Global Analysis and Assessment of Sanitation and Drinking Water (GLAAS) 2021/2022 survey found that 29% of all water and sanitation expenditures are funded by governments (see Figure 3). This survey, while not specific to SWP and diversification, highlights the important role that funds from regional and central governments play in the sector. Funding from both regional and central government levels has been used to cover a range of costs for SWP and diversification, including large infrastructure projects and watershed management. For example, in Addis Ababa, most SWP and diversification funding is concentrated at the federal level from large reservoir projects to the three-year Addis Ababa River Side Project (2020-2023) that aims to clean the rivers and expand green development efforts (Doyle 2020). In Ethiopia, researchers have noted that while the federal government has greater access to financing, a drawback of federal government funding is that local water authorities and

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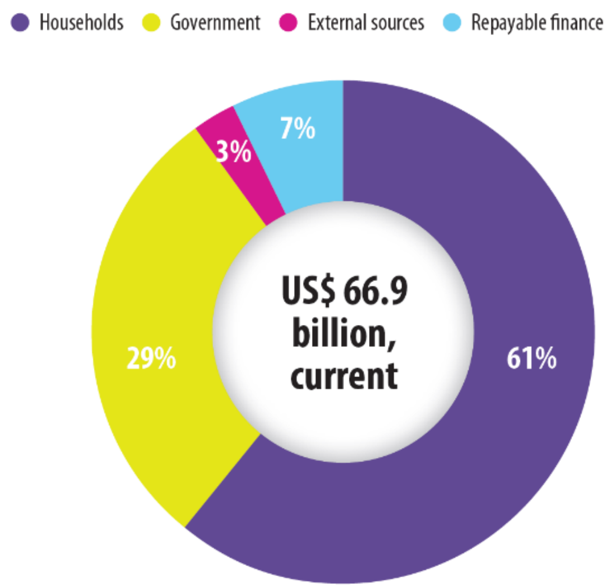
23 A "non-capital operating ratio" is simply the annual revenues divided by annual operating expenses, without including depreciation. An "operating ratio" or "full operation ratio" is the annual revenues divided by operation and maintenance expenses plus depreciation (Kleven 2014).

communities play a limited role in funding allocation and decision-making for water projects (Tamrat 2008).

Figure 3. Sources of funding for water and sanitation



(WHO 2022)

Repayable financing mechanisms

Loans or bonds are extremely common methods of financing the construction of large infrastructure projects, including pipelines to transport water from new sources over long distances, groundwater pumping infrastructure, desalination infrastructure, and wastewater treatment. Loans and bonds may include concessional loans, low interest government loans (such as revolving fund loans), commercial loans, and municipal bonds. In the United States, many water and wastewater projects are funded by municipal bonds, which are sold and traded in the open market and offer investors the tax benefits (U.S. Securities and Exchange Commission 2018). Across the case studies, loans for SWP and diversification have been used to construct reservoirs, pipelines, and wastewater treatment plants, including a $150 million loan from China to increase water supply for Lusaka through the Bulk Water Supply Project, a $87.1 million loan from the Inter-American Development Bank (IDB) for pipelines to reach new water sources for Quito and increase system redundancy in its metropolitan area, and World Bank funding of water and wastewater projects in Ethiopia, including a $6 million loan for wastewater treatment in Addis Ababa (ADF 1995; "Ecuador to Improve Drinking Water and Sanitation Services with IDB Support" 2019; LWSC 2020). CWAs in LMICs have traditionally had access to concessionary debt, but as they reach higher levels of creditworthiness and technical capacity, they can access commercial loans, municipal bonds, or green bonds (USAID 2021b). For example, Manila Water Company, Inc., a private utility, has secured several consecutive 10-year loans with various foreign and domestic banks, ranging in value from $52–150 million to finance their CAPEX plan (Manila Water Company Inc. 2022).

A bond is a market-based instrument used by issuers (e.g., governments, corporations, etc.) to raise money from investors. Green bonds were created to fund projects with environmental and/or climate benefits, including water resources management projects. They are becoming increasingly popular as investors seek to align their financial portfolios with sustainable development goals, and as governments, utilities, and multilateral development banks look for innovative ways to finance climate adaptation and mitigation activities. The first green bond issued in an LMIC took place in South Africa in 2012 and was issued by the state-owned Industrial Development Corporation for clean energy infrastructure (Otek et al. 2021). Since then, the green bond market in LMICs has grown exponentially, with the East Asia and Pacific region driving its growth and accounting for 81% of the market (or $315 billion in 2018) (Otek et al. 2021). In recent years, blue bonds have emerged as another means of financing sustainable development initiatives, specifically for water-related projects, such as improving water supply and sanitation systems, reducing water pollution, restoring wetlands and other aquatic habitats, as well as marine and ocean-based projects. Given their relative newness, limited research is available on blue bonds markets and their potential applicability for SWP and diversification in LMICs.

Public-Private Partnerships (PPPs) are long-term arrangements with private sector entities that invest in infrastructure and operation of water systems and recover their costs through user fees. Water and wastewater projects make up the smallest portion of PPP markets as compared with transportation and energy projects, as they tend to have lower profit outlooks (Habtemariam et al. 2021). PPPs have been used to fund large SWP and diversification infrastructure projects, for example to secure new water resources or for wastewater treatment. Two of the case studies included PPP arrangements: Manila and Amman. In the case of Amman, the large, multi-beneficiary infrastructure project to transport water from the Disi Aquifer was set up as a build-own-transfer PPP.

Under the Metro Manila Concession PPP, according to the Revised Concession Agreement, the MWSS assigns the two concessionaries the "rights and obligations solely in relation to the service area… source raw water from catchment areas, watersheds, springs, wells and reservoirs in the service area, subject to the applicable authorizations from the relevant Government Authorities" (MWSS 2021). Although historically, this language has left room for interpretation, in practice, MWSS requires its two concessionaires to include investment in watershed protection in their business plans. While both concessionaires did invest in a reforestation program, PPPs are private sector investments, whose purpose is to recover investments through projected income (normally from water user fees), while minimizing risks to investors. Therefore, it is not surprising that PPPs are not generally used to mobilize investment in long-term watershed protection whose outcomes have a high level of uncertainty.

Non-repayable financing mechanisms (grants)

Grants, including foreign aid (or development assistance) and grants from non-governmental organizations, as well as support from organizations such as universities have been successfully used for a variety of SWP and diversification activities. Grants have been used both to fund large-scale investments—such as the MCC project in Zambia that restored the Lolanda Water Treatment Plant (MCC 2020)—and to fund small-scale technical assistance that improves efficiency and enables CWAs to access new sources of funding.

Advantages of grant-funded projects are that they clearly enhance existing funding sources, can be used to leverage other funding sources, and fund projects that are particularly difficult to fund with other financing mechanisms. However, grant funding is temporary and not sustainable in the long term, and like financing through national-level programs, most grants are not locally managed. Key informants in Lusaka voiced concerns over the autonomy of CWAs to define funding priorities and project relevance as many funds from international donors have very specific terms and are carried out mostly by international partners (KI Lusaka 2022).

Innovative financing mechanisms specifically designed for watershed protection

Payment for Environmental Services, or PES, are flexible mechanisms of monetary compensation for the purpose of maintaining or providing an environmental service, for example to conserve and/or restore watershed ecosystems that provide greater availability and/or quality of water for downstream use. In terms of protection of source water quality and quantity, these arrangements are appropriate when they involve upstream and downstream users. They may take the form of private PES projects, such as purchase of upstream land for protection of watersheds, pollutant cap and trade projects, or public PES projects involving taxes and subsidies (IUCN 2012; Salzman et al. 2018).

Two types of PES schemes have been widely used in LMIC settings for SWP: government-subsidized PES programs (simplified as PES) and water funds.

Government-subsidized PES. Watershed PES programs involve cash and/or in-kind compensation of upstream watershed landowners or land users in compensation for adopting sustainable practices that ensure ecosystem conservation and environmental restoration. PES schemes are often subsidized with government funds to get started; however, they can be funded through multiple sources, including private sector and water users' contributions. Over 250 government-subsidized PES programs have been implemented in 39 countries, with particularly strong experience in China (69 programs) and Brazil (66 programs) (Mamedes et al. 2023; Salzman et al. 2018). While there are many examples of successful PES projects, not all of them have been fully successful. In an evaluation of 40 such projects that had sufficient information to gauge results, 23 were classified as successfully meeting project objectives and adding overall value to the region, 12 partially successful, and five unsuccessful (Grima et al. 2016). Sometimes negative or unexpected effects of these projects have occurred, including: (1) implementation of the PES schemes did not achieve desired results, (2) local livelihoods did not improve, (3) abandonment of traditional productive activities, (4) conflicts, (5) resistance to PES, and (6) environmental degradation. The effects of these programs depend on the local context, including social, institutional, economic, and environmental conditions (AfDB 2015; Calvet-Mir et al. 2015; CGIAR 2020; Grima et al. 2016; Nam and Endo 2021; Perevochtchikova et al. 2021; Seroa da Motta and Ortiz 2018; Tetra Tech and LTS Africa Ltd 2018; To et al. 2012; Turpie, Marais, and Blignaut 2008; Ureta, Abueg, and Inocencio 2021). Government-financed PES arrangements tend to be less sustainable than other types of PES arrangements, as they depend on financing from general revenues, cover larger areas, and are subject to political risk (Young 2000). Although only one of the case study cities, Sao Paulo has an active government-financed PES; there are many more of these programs than water funds, in part because they take less time to establish and begin implementing.

Water funds (sometimes termed as **collective action watershed PES**) have also gained traction globally to fund SWP efforts. Water funds are financial and governance mechanisms that unite public, private, and civil society stakeholders around a common goal to contribute to water security through NBS and sustainable watershed management. They are specifically designed for SWP, where the primary source of potable water is surface water, and they focus on watershed protection. Water funds have been promoted worldwide, particularly by TNC.

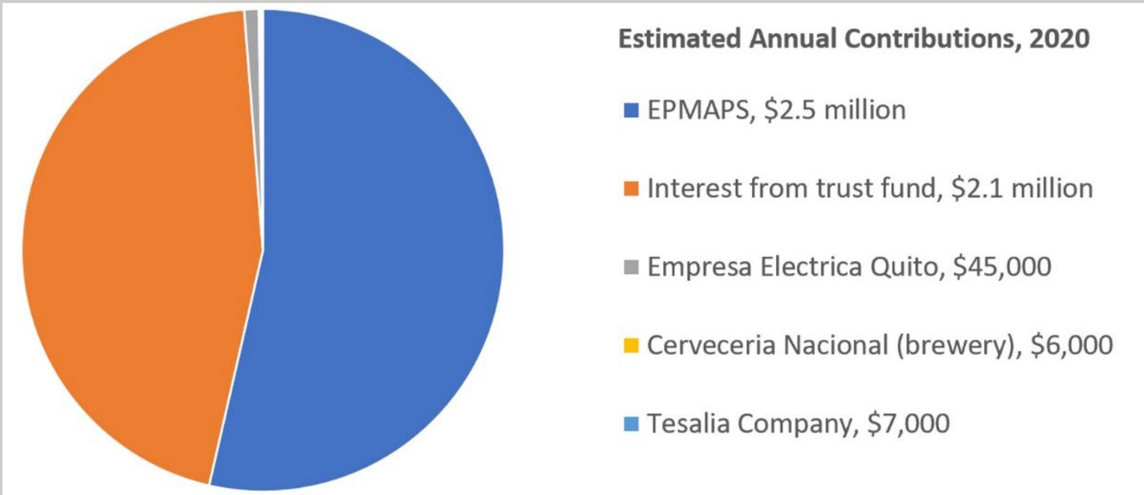
As water funds imply the creation of a new organization, they are most relevant in locations where no other watershed management arrangement has been formally established (Lamus 2021; TNC 2023a). As of 2022, TNC had facilitated the establishment of 43 active funds in 13 countries, with 35 more under development. Of the active funds, 26 are in Latin America, 13 in North America, eight in Africa, and two in Asia-Pacific (TNC 2023a; 2023b).

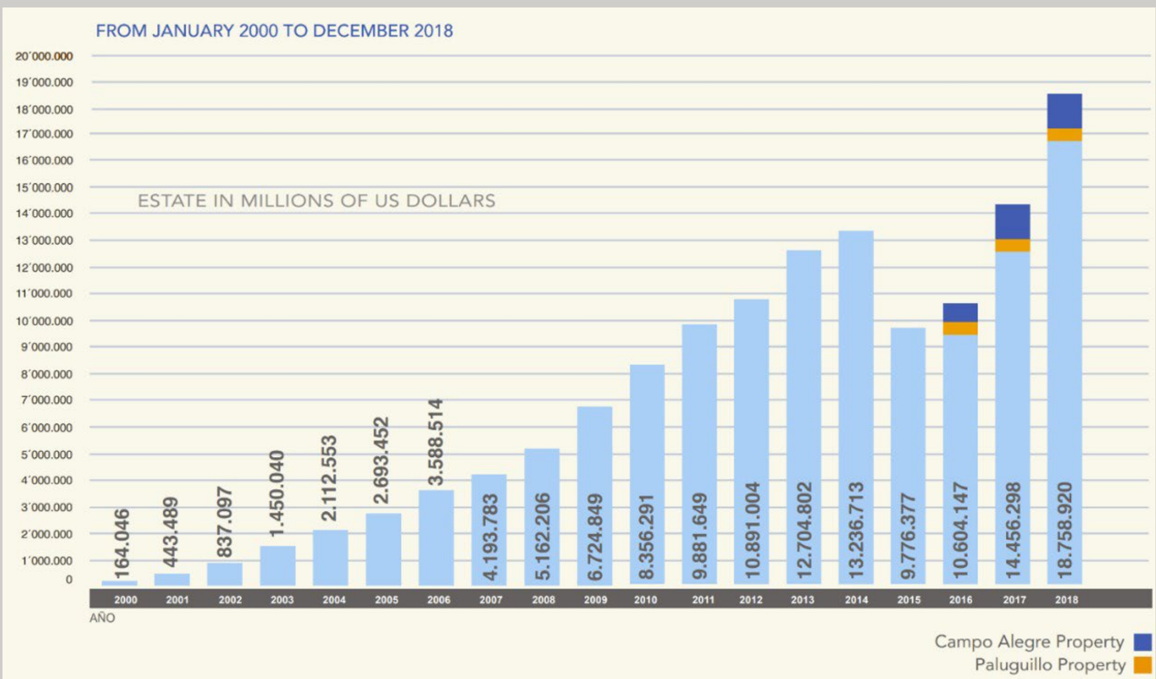
Water funds often involve multiple entities, with high initial transaction costs, and they require patience; it typically takes several years (four to five) to set them up, and another five years to build up a strong fund. Their structure is sustainable over the long term, and their results must be gauged over long time frames (Bonthuys 2019; Herrin 2018; TNC 2015). Water funds have been successfully created and used in three case study cities: Quito, Sao Paulo, and Cape Town (TNC 2023a). In Cape Town, the Table

Mountain Fund, established in 1998, has supported initiatives to restore the natural ecosystems that supply water to the city and surrounding areas. The fund operates through contributions from individuals, organizations, and businesses and has funded projects such as alien vegetation clearing, wetland restoration, and river rehabilitation. In São Paulo, the Cantareira Water Production System, which supplies water to over nine million people, established a water fund in 2014 to support the conservation and restoration of the surrounding forests and rivers. The fund operates through a PPP and has raised over $20 million, which has been used to support projects such as reforestation, soil conservation, and riverbank stabilization. Both funds have been recognized for their innovative approach to financing and managing water resources and for their potential to serve as models for other regions facing similar challenges. Quito has been particularly successful, as noted in Box 14.

Box 12. The FONAG Water Fund

FONAG, the water fund that protects the watersheds serving the Quito area, was initially established in 2000, with support from TNC and the Swiss Development Agency as a PPP to support the conservation of the Andean paramo ecosystems that provide water to the city of Quito and surrounding areas. The fund operates through contributions from a range of stakeholders, including local governments, water utilities, private companies, and civil society organizations. By 2020, the fund had grown to over $28 million, and the annual budget to $3.5 million.





Coronel T. 2019; EPMAPS 2019; FONAG 2022

3.3.2 FINANCING CHALLENGES AND ENABLING FACTORS FOR SUCCESS

CWAs in LMICs face significant challenges in accessing financing for SWP and diversification, limiting implementation of these measures to improve the resilience of urban water supply. These challenges often begin with insufficient tariffs to cover operating costs, which is typically due to system inefficiencies, as well as low stakeholder and decision-maker support of SWP and diversification and limited local control over funds. Factors that have enabled cities to overcome these challenges common to most financing sources include: (1) strong leadership and political commitment, (2) clear understanding or benefits and tradeoffs, (3) involving key stakeholders early when designing financing arrangements, (4) addressing non-revenue water (NRW), (5) implementing structures and systems to decentralize fund management, and (6) responsible and transparent fund administration.

Tariff revenues are insufficient to fund SWP and diversification measures

The principal challenge to use of CWA annual operating budgets for SWP and diversification is that most utilities in LMIC settings do not have sufficient revenues to cover their first priority for use of these funds: operation and maintenance of existing systems (Habtemariam et al. 2021; OECD and UNCDF 2020). Repayable financing mechanisms require water tariff and fee structures that cover loan payments; generally speaking, a CWA would ideally have an operating ratio of 1.2 to be deemed financially viable for repayable financing options (Kolker et al. 2016).

The ability of tariff revenues to cover costs, or to achieve a revenue-cost ratio to make debt service payments is related to many factors, including households' ability to pay, the administrative and management efficiency of CWAs, and the infrastructure and technology required to provide freshwater resources. Water utilities that have been able to achieve higher revenue-cost ratios have implemented strategies including increasing rate collection, improving overall system management efficiencies and reducing costs, reducing NRW, and raising tariffs (Kolker et al. 2016; USAID 2021b).

Among the case study cities, those with lower levels of NRW (such as Sao Paulo and Quito) have been able to secure more resources for SWP and diversification. Addressing NRW includes increasing tariff collection rates, limiting illegal connections, and decreasing leakage. Cities that do not address leakage will have higher needs for potable water and need to invest more funds than otherwise in source water diversification—for example, to drill new wells, construct new reservoirs or dams, build new water treatment infrastructure, or purchase additional water from neighboring areas.

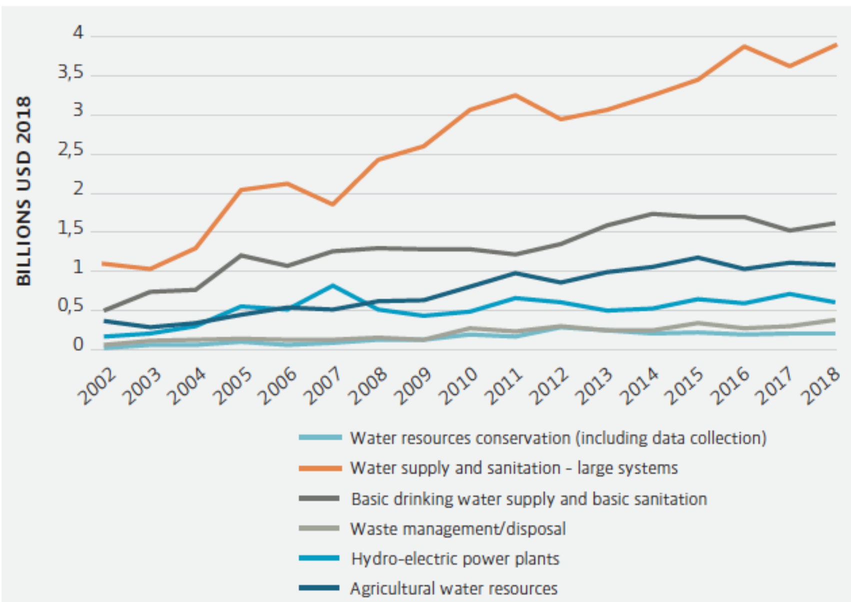
A key strategy that enabled CWAs in the case studies to increase access to funding resources beyond tariffs was to use a combination of funding sources and financing mechanisms for SWP and diversification. This could include involvement of the central government for loan guarantees, or, as is the case in Addis Ababa, by designating the central government as the entity responsible for loan payments (USAID 2021b). However, over-reliance on central government-funded projects and programs creates risks due to limited resources, limited local control over resource allocation decisions, political risk, and relatively short (often three-year) duration of funds (Doyle 2020; Tamrat 2008; WHO 2017; Young 2000).

Low stakeholder support and prioritization of source water protection and diversification

It is widely recognized that the water sector is relatively under resourced and under prioritized by governments and funders. AfDB notes that Africa will need to spend at least $130 billion on water and sanitation infrastructure in order to meet the SDG goal of universal access to water and sanitation, but it faces a financing gap of $68–108 billion (AfDB 2018). These figures do not include watershed protection, and as demonstrated by the statistics across water-related Official Development Assistance (ODA) from 2002–2018, the proportion of funds dedicated to water resources conservation have been decreasing relative to WASH investments (OECD 2022; UN WWAP/UN-Water 2018) (Figure 4).

Strong public support and a strong tax base are associated with higher central and regional funds available for SWP and diversification projects. It is possible that studies that estimate the economic value of water can positively influence both international- and country-level prioritization of investments in water. Using the economic value of water as a basis for water allocation can lead to higher allocations to cities and lower allocations to agriculture (Reznik et al. 2016). This approach has also been used to evaluate different options for diversification (Reznik et al. 2016; World Bank 2022b). In the case of Rwanda, which looked at the role of storage through a linked macroeconomic model and WEAP, the macroeconomic gains far outweighed the investment. There is some promising work in linking national-scale physically based water and energy models with macroeconomics in Central Asia through USAID's Regional Water and Vulnerable Environment Activity that shows the impacts of investments across sectors on national GDP.

Figure 4. ODA Investments in the water sector by type of project



(OECD 2022)

Communication about the impacts and tradeoffs between SWP and investment in other water diversification options, as well as clear communication on expected time frames over which benefits of SWP may be expected, is a critical enabler of stakeholder buy-in. Therefore, despite the difficulty of determining the costs and benefits of SWP, context-specific methods should be used to estimate its value. Analysis of tradeoffs between green and gray investments has fostered support for investment in green options, and analysis of tradeoffs between different watershed protection options has helped to target resources to higher impact investments. However, often trade-off analyses of SWP and diversification options are conducted with a limited scope, such as trade-offs between different watershed protection options, or between different options for augmenting water supply (as is typical in water system master planning studies) without consideration of resilience in the face of climate or other risks. Rarely have tradeoffs between investments in a wide range of green and grey investments and strategies and options been compared that include less-conventional approaches such as demand-side management, water markets, wastewater reuse and watershed protection. Additionally, analysis of tradeoffs between different watershed protection options has helped to target resources to higher impact investments.

For example, in Quito, investments from the Environmental Fund for the Protection of Basins and Water (FONAG) were used to carry out surveillance programs that increased soil and water monitoring to analyze the impacts of the initiatives and better target areas for improvement. This allowed the fund to demonstrate effectiveness to stakeholders, thereby building trust and accessing additional investments (Ertel et al. 2019). Local issues that will affect the calculated impacts of watershed conservation include land ownership, predominant current and alternative economic activities and land management practices, land stewardship arrangements, the baseline ecological state, geomorphology, and climate.

Tools and information to analyze watershed management options are increasingly accessible to middle- and lower-income municipalities. For example, a study by Vogl and Wolney (2015) highlights the value of the Resource Investment Optimization System, a free and open-source software tool for targeting investments in soil and water conservation activities with the goal of achieving the greatest ecosystem service returns toward multiple objectives. Another study used a multicriteria evaluation in GIS environment combined with land use economic analysis to determine priority areas and opportunity costs for PES investments (Souza, Dupas, and da Silva 2021).

Limited local control over resource decisions

The issue of limited ability to make long-term plans and lack of control over resource decisions as a challenge came up in key informant interviews for the CWAs most dependent upon grants from external sources, including central government resources for funding SWP and diversification. For example, in Lusaka, there had been plans for diversification in place, but the resources to support that plan depended on decisions by the national government and donors, and only with a crisis were funds made available.

There are many ways that central governments have targeted resources to cities while giving cities decision-making power on how to use the resources. For example, the Constituency Development Fund of Zambia is set up such that local authorities choose projects that are spending priorities in their communities as identified in community-level Integrated Development Plans (Silimina 2022). Another example is the State Water Resources Fund (FEHIDRO) of Brazil, which provides low interest loans or grants for projects and activities approved by River Basin Committees (Johnsson and Kemper 2005; Silva 2017). In the United States, the Environmental Protection Agency provides grants and loans for pollution prevention, including wastewater treatment, to states, inter-state agencies, and tribes.

Another method that has been used to increase local control over resources and enhance long-term planning of water resources is to foster regional institutions that manage natural resources. This is a widely implemented strategy for watershed management that has been implemented worldwide. One method to fund these institutions is a surcharge or tax for watershed management, as described previously (Section 3.4.1).

Challenges and enablers for PES and Water Funds

Studies evaluating success factors of PES projects in Latin America have shown mixed levels of success, and do not use consistent definitions of success. The study evaluating 40 PES projects in Latin America used two criteria for categorizing "success;" the extent to which projects met stated objectives, and the extent to which projects contributed positive impacts beyond its stated objectives (Grima et al. 2016). In another study evaluating 54 water PES projects in Brazil, 31% of active projects were not making payments (Mamedes et al. 2023). Two challenges faced by PES projects (in addition to those described below) are unanticipated opportunity costs to landowners and unequal access to payments. Two

Brazilian cases that illustrate the set of challenges and success factors of PES projects are described in Box 15.

Box 13. Successes and Challenges of Brazil's Water Producer Program

Brazil is one of the countries with the highest number of PES programs in the world; it launched 80 programs between 1997 and 2021, of which 54 projects are in the Water Producer program developed by the national water agency, ANA. It is also the country in which most studies evaluating the successes and challenges of watershed PES programs has been evaluated (Grima et al. 2016; Mamedes et al. 2023). The following two examples illustrate some successes and challenges of the program.

The Piracicaba-Capivari Jundiai Watershed project, launched in 2009, faced many challenges. Funded practices included fence building, planting native trees in riparian areas, construction of terraces and rainwater infiltration holes, and implementation of no-till farming. The project suffered from low participation, in part due to mistrust based on the low value of PES payments, lack of flexibility in use of PES funds, issues with documentation to prove land tenure, and mistrust of the capabilities of those aiding. The project used an intermediary and suffered from logistical issues and poor understanding by stakeholders of the time expectations for benefits. No data was collected to confirm whether the implemented practices improved water quantity or quality (Viani et al. 2019).

The Extrema Water Producer program, evaluated 10 years after its establishment in 2015, on the other hand, reforested 216 ha and conserved 6,378 ha of Atlantic Forest as of 2016 (Ozment et al. 2018). Success factors cited were support from national water policy, studies that modeled the potential benefits of the program, a strong commitment from the municipality, a network of experts in universities and civil society that provided monitoring and technical capacities for use in planning and implementation, and a strong tax base for the PES program from a robust industry combined with a high industrial tax rate (Richards et al. 2015).

These studies also noted that there is no standard criteria for evaluation of success of PES projects and that there is limited information on the extent to which projects meet stated objectives or make disbursements to upstream users (Viani, Bracale, and Taffarello 2019). As less has been published on the success of water funds, key informant interviews were the primary source for analysis of challenges and enablers for water funds.

Trust, leadership, and political commitment

Strong leadership, trust, and political commitment were found to be an important enabling factor for successful planning and implementation of both PES programs and water funds. For example, stakeholder engagement early on, including engagement of Indigenous people, was associated with more successful projects. Exemplary projects within a country led to support for implementation of projects in other locations, while inappropriate expectations led to project failures. PES programs that use in-kind contributions rather than cash had lower failure rates as a result of increased trust and reduced perception of opportunities for corruption (Coronel T. 2019; Grima et al. 2016; Mamedes et al. 2023; Viani, Bracale, and Taffarello 2019). One study stated that, "in cases in which resource stewardship is provided at the community level, fair and transparent systems are needed to avoid corruption and to disperse revenue to individual beneficiaries or legitimate community level investments" (Milder and et al. 2010).

Time and legal frameworks required for water funds

Challenges of water funds are the high initial transaction costs and associated time that it takes to legally establish a fund, and the time that it takes to grow the fund to a size that yields substantial income. It took four years to establish the FONAG water fund benefiting the Quito Metropolitan Area, during which changes occurred in country leadership. To implement successful watershed protection and restoration projects in general, and to work most effectively at the community level, both FONAG and the Cape Town water project found that water funds that establish agreements with long time frames (10 years or more) were critical to enable sustained measures and build community trust. FONAG's close relationship has evolved into formalizing long-term, 10-year agreements with stakeholders, which allows funds' users to adapt and respond to local priorities and ensures their buy-in (KI Quito 2022a, 2022b). Cape Town has committed to incremental implementation of source water improvements, meaning projects are planned over multi-year timeframes—usually 10 years—to maintain sustainable funding and allow for time to build trust with stakeholders via communication of project goals and interactions with affected communities to understand their needs and realities (City of Cape Town 2019; Stafford et al. 2019).

A challenge that FONAG has faced is its limited legal mandate to protect the watersheds such that water quality and quantity is maintained or improved for human use. As a result of this limited mandate, FONAG is not charged with ensuring that ecological flows are maintained in rivers downstream of withdrawal points, and its support of municipalities and communities that benefit from watershed protection has been limited to capacity building and minor investments. Municipalities in the watersheds east of Quito strongly expressed concerns that they have not been sufficiently consulted or compensated; they have lobbied for more support for new and existing small potable water systems that serve their communities, many of which lack adequate infrastructure and water treatment. FONAG's mission is to protect the watershed, and the mission of *Empresa Pública Metropolitana de Agua Potable y Saneamiento de Quito* (EPMAPS)[24] is to provide potable water service to the residents of its service area, creating competing priorities.

Table 9 provides a summary of the challenges and enabling factors for PES schemes and water funds.

Table 9. Challenges and enabling factors for PES schemes/water funds

	Characteristics of PES Schemes with Lower Rates of Success (Challenges)	Characteristics of PES Schemes with Higher Rates of Success (Enabling Factors)
Both PES and Water Funds	• Mistrust • Inappropriate expectations of time frames for results • Cost-benefit not clearly determined or communicated	• Stakeholder engagement • Leadership and political commitment • Exemplary projects in country • Trade off analyses
Specific to water funds	• Legal frameworks to set up • Time to grow fund	• Projects operating with a 10-year or longer time frame
Specific to subsidized PES	• Existing land rights arrangements and power structures were threatened • Inequitable access to payments and/or people perceived or observed unfair practices in the distribution of (particularly cash) benefits • Lack of transparency • Opportunity costs to landowners did not clearly favor participation	• The use of in-kind contributions rather than cash payments • Engagement of upstream land users early on, particularly including indigenous people

Sources: Grima et al. 2016; Latin American Water Funds Partnership 2022; Coronel 2019; Mamedes et al. 2023; Perevochtchikova et al. 2021; Ribeiro de Souza, Antonio Dupas, and Aparecido da Silva 2021; Viani, Bracale, and Taffarello 2019

[24] EMPAPS is the municipal unit in charge of water management in the metropolitan district of Quito.

3.3.3 CONCLUSIONS ON FINANCING FOR RESILIENT URBAN WATER SUPPLY

Financing remains a serious challenge to the realization of SWP and diversification projects, especially in LMICs. Efficiently run, profitable CWAs, particularly in middle-income countries and locations where water costs are low, tend to have a higher ability to cover operation and maintenance costs with tariffs and to implement tariff surcharges to fund SWP and diversification projects. They can also implement a greater variety of financing models, including access to loans and bonds, and depend less on external funding sources. CWAs in lower-income settings and in settings with scarce water resources where the cost of water is high, however, often struggle to even cover basic operating costs, and therefore have lower access to loans and private investment and rely more heavily on grant funding. PES schemes and water funds are emerging as innovative financing mechanisms that bring in new funding sources, such as private sector contributions and interest income, which can be used to fund SWP and diversification projects. Table 10 provides a summary of the types of SWP and diversification activities typically funded by different mechanisms.

Table 10. Financing mechanisms for source water protection and diversification measures

Urban Water Supply Improvement Solutions	Level of Investment	Successful Financing Models						
		CWA Annual Budget	Loans or Bonds	Regional or Central Government Programs	PPPs	Government-Financed PES	Water Funds	Grants from External Sources
Source Water Protection								
Forest and watershed conservation and reforestation	$$	●		●		●	●	●
Wetland conservation and restoration	$$			●	●	●	●	●
Green agricultural practices	$		●	●		●	●	●
Green stormwater management	$	●		●	●			
Land use policies, plans, and implementation,	$			●		●	●	●
Wastewater permitting	$			●		●	●	●
Purchase of land for conservation	$$$					●	●	●
Public education	$	●		●	●	●	●	●
Wastewater treatment (construction)	$$$		●	●	●			●
Dry latrines, septic tanks, other onsite systems	$$	●	●	●	●			●
Wellhead protection	$$	●		●	●	●	●	●
Modeling and impact evaluation	$	●		●	●	●	●	●
Diversification								
Demand management (water conservation/reduction in water use rates)	$$	●		●				
Reduction in leakage	$$	●	●	●	●			
Infrastructure to secure new surface or groundwater resources	Varies	●	●	●	●			●
Water storage infrastructure, including reservoirs	$$$		●	●	●			
Planning and modeling, including risk assessment	$	●	●	●				●

Urban Water Supply Improvement Solutions	Level of Investment	Successful Financing Models						
		CWA Annual Budget	Loans or Bonds	Regional or Central Government Programs	PPPs	Government-Financed PES	Water Funds	Grants from External Sources
Unconventional water sources (including desalination, stormwater/wastewater/greywater reuse, rainwater catchment, etc.)	Varies	●		●	●			●
Groundwater management and managed aquifer recharge	$$	●	●	●	●			●
Emergency systems, structures, and equipment	$$	●	●	●				●
System redundancy and inter-connection infrastructure	$$	●	●	●	●			
Water banking/water trading	$	●		●				

Sources: Habtemariam et al. 2021; IUCN 2012

The "best" set of financing alternatives for a particular city will depend on income levels, the type of SWP or diversification approach, and on the local context. CWAs need better understanding of the types and combination of funding sources required for specific SWP and diversification interventions given the legal-regulatory-institutional setting, scale, and financial standing, among other factors. A foundational challenge that limits CWAs' access to appropriate financing is the lack of prioritization of SWP and diversification. Evaluation and communication about the impacts and tradeoffs of different SWP and water diversification options and the expected timeframes over which benefits of projects may be expected are essential for stakeholder buy-in. Approaches to estimating and communicating these costs, benefits, and trade-offs for stakeholders to facilitate their decision-making process still need to be better understood. Innovative financing mechanisms such as PES, water funds, and the green and blue bonds that have emerged as alternative funding sources for SWP and diversification require further investigation to better understand their potential applicability across LMICs.

4.0 RECOMMENDATIONS

By examining research questions on the planning capacities, negotiation strategies, and finance mechanisms that CWAs have used to successfully implement SWP and diversification solutions, along with specific challenges and enablers in LMIC contexts, this study points to strategies that development partners can use to better support CWAs to achieve resilient water supplies. The case studies and literature highlight important considerations that partners must consider prior to designing SWP or diversification projects.

This final section of the report provides recommendations for stakeholders involved in decision-making for SWP and diversification, development partners, and researchers.

4.1 PLANNING

The selected case studies provide examples of successful planning and action to mitigate risks to water resources. These provide valuable lessons to city authorities and development partners who seek to support better risk-based planning efforts, although gaps in understanding remain.

Prior to supporting planning processes, it is critical for partners to understand what institution is responsible for water allocation, what planning processes are already in place, and what tools and data exist and are used to inform those processes.

A wide range of planning frameworks and modeling tools are available, but external actors should be careful to select approaches that align with local systems and capacities. To effectively participate in planning, cities and utilities need to be able to forecast demands and risks. Where planning does not sufficiently address climate change and other uncertainties, partners can support utilities and/or basin authorities to access data and tools tailored to the local context and by building the technical capacity required to sustain planning efforts. This may require working with local institutions to support investment in monitoring and data management systems that can be sustainably managed locally.

Planners and water authorities should work to foster participatory engagement in planning efforts.

Collaborative planning has been shown to achieve both more equitable outcomes and more resilient bulk water supply. If existing planning processes do not include stakeholder engagement, partners can work to build capacity and facilitate engagement to demonstrate its value. Engaging a wide array of stakeholders helps foster a more holistic view of water use in an area by bringing together diverse water users and facilitating cross-sector dialogues. Development partners can play a facilitative role by bringing together the different stakeholders, particularly by bridging the gap between those focused on water services and those focused on WRM and between those who work at different geographic scales.

Cities take advantage of crisis situations to catalyze long term planning.

Across the case studies, emergencies such as water shortages, disease outbreaks, and rapid population growth often triggered action on managing source water supplies. Cities can leverage public attention and emergency funding to lay the groundwork for longer-terms water resource management, such as by institutionalizing demand management, diversifying water sources, and source water protection measures. Partners can support city planners by assisting leaders to frame SWP and diversification options as solutions to current or potential crises to build support for these options.

Evidence Gaps

While the literature and case studies provided evidence on the frameworks, tools, and approaches that have been used for planning SWP and diversification activities, planning exercises in LMICs are still largely externally driven. Further research is needed to better understand what drives uptake of these tools by CWAs and how approaches can be better adapted to their needs.

Incentives and motivators for decision-maker uptake of climate and uncertainty planning for SWP and diversification

CWAs in low-resource settings often do not consider SWP and diversification to proactively reduce risk to water supply, with actions only occurring after a crisis hits or due to a project supported by an external actor. However, studies that demonstrate the potential benefits of SWP have led to increased stakeholder and decision-maker support and resource allocation. Further research is needed to understand how CWAs and other government actors can be motivated or incentivized to proactively consider risks and plan for resilience. This will require a better understanding of how risks, costs, and benefits are assessed and communicated to relevant stakeholders, as well as what tools can be used to persuade decision makers to plan for uncertainty.

Understanding of how to select and adapt planning frameworks and data tools for multiscale, multi-stakeholder, complex institutional decision-making in low-resource settings

In many studies, there is very little documentation of the existing data collection, management, and modeling processes, making it difficult to understand how new tools fit into CWAs' current operations. Many examples of successful SWP and diversification in LMICs merely report on the outcomes of planning studies but do not evaluate how planning frameworks and tools were selected, how the information produced by these tools was used, whether these tools provided the best outcome for the CWA, or whether CWAs continued using tools or frameworks following interventions. Further documentation of use of these frameworks in LMIC CWAs would allow for a better comparison between frameworks and their effectiveness.

4.2 NEGOTIATION

The "best" choice of negotiation method will vary based on the scale and political clout of the city, institutional arrangements for WRM and water supply, water allocation mechanisms, and the presence of transboundary issues.

Although the literature and case studies show that incentivization, trusted intermediaries, and public buy-in can be successful methods for fostering productive negotiation, partners aiming to support negotiation processes must understand local systems for water allocation or water tenure, including formal water rights as well as customary, informal, and even illegal arrangements. It is also critical to understand the relationships between competing stakeholders, including the legal responsibilities, power dynamics, prior history, and economic systems that drive water allocation and use, before attempting to structure incentives or strengthen institutions as further described in USAID's Water Security, Sanitation, and Hygiene Governance Technical Brief. Unequal power dynamics, conflict between sectors and across administrative boundaries, and policy fragmentation can all hinder progress. To avoid creating dependencies, rather than playing a direct role in negotiations, partners should seek to identify trusted intermediaries that could broker partnerships or incentives that could motivate agreements between competing water users, while being cautious not to duplicate existing efforts.

Evidence Gaps

While the literature and case studies provided evidence on the types of negotiation methods, key challenges, and enablers that CWAs have used to advocate for investments in SWP and diversification measures, the effectiveness, process, and clear outcomes from the use of these negotiation methods across different LMIC contexts have not been well documented in the literature. In particular, more information about how incentives can be structured in low-resource settings is required.

Incentivization and water markets in low-resource settings

The use of water markets and other financial incentives as negotiation mechanisms have gained traction globally in high-resource contexts and some LMIC contexts. However, CWAs often lack the financial resources to use this negotiation mechanism. In addition, though effective, incentivization presents the risk of market power formation if not monitored and regulated adequately. This inherently requires sufficient monitoring and enforcement capacity. Further research is needed to better understand how incentive structures can be set up in instances where finances are limited, or when financial incentives may not be an option, and how incentive mechanisms can be appropriately designed, structured, and implemented to mitigate potential market distortion.

4.3 FINANCE

This desk research provided evidence on financing models that have been applied successfully for protecting source water and achieving resilient water supplies through diversification, their pros and cons, and factors that can contribute to or inhibit their success. Key lessons from these cases align with existing guidance for mobilizing finance for utilities (World Bank 2018; USAID 2021b). There are, however, evidence gaps that warrant further investigation to demonstrate their applicability across different LMIC contexts.

Utilities should focus on the necessary performance and efficiency improvements to achieve creditworthiness before aiming to mobilize finance for SWP.

Utilities typically prioritize covering operations and maintenance costs and expanding services before investing in SWP and diversification, so partners should focus on creditworthiness before aiming to support utilities to mobilize finance for SWP. Further guidance on how utilities can achieve capacity and efficiency improvements by applying commercial principles is available in USAID's Urban Water Services Technical Brief. However, given that even many well-performing utilities do not prioritize SWP among competing priorities, partners may need to help build the case for such investments through studies that analyze watershed management options and compare the costs and benefits of SWP with other options to improve water supply quantity and quality.

Stakeholders must consider utility performance, governance systems and the type of SWP or diversification project to be financed when assessing the feasibility of accessing different types of financing.

Given that the "best" source of finance will vary depending on the utility's performance, local governance systems, regulations, and the type of SWP or diversification project, stakeholders must consider these factors in assessing the feasibility of accessing different types of financing and the long-term reforms that may be necessary for sustained financing (see USAID's Financing Water and Sanitation Services Technical Brief for more guidance on assessing different types of finance for water). When supporting financial structures designed specifically to finance SWP, it is important that stakeholders ensure that: 1) lessons learned from similar projects are carefully considered, 2) expectations of the timeline for impacts are clear to all stakeholders, and 3) long-term local support is secured given that financing mechanisms such as PES and Water Funds can take several years to establish and even longer before they provide a sustained source of funding.

Evidence Gaps

Finance mobilization for SWP and diversification

Cities in LMICs do not prioritize investments for SWP and diversification under normal circumstances as they lack information demonstrating both the potential and actual benefits, including socio-political benefits. Poor documentation of the baseline conditions and changes over time, combined with misunderstanding of the timeframes over which benefits would be achieved lead to challenges in mobilizing funding and sustaining stakeholder support for SWP and diversification projects. In addition, estimates of financial benefits generated in data-scare environments are often unrealistic, either over- or understating the potential benefits. Tools and information to analyze options are increasingly accessible to middle- and lower-income cities but have limited uptake, unless driven by external actors. A better understanding of how CWAs can effectively quantify the costs and benefits of SWP and diversification projects would enable them to better select appropriate interventions and justify investment.

Challenges of water funds and PES in LMIC settings

Water funds and other PES programs have demonstrated successes and limitations in various contexts. Studies evaluating watershed PES programs indicate that many programs have been successful overall, but that there are many lessons learned, and that sharing of experiences would be worthwhile. Most studies of PES come from Latin America, with limited evidence of whether similar lessons would apply in other geographies. Additionally, there are limited examples of applications in small- and medium-sized cities. Water funds have also been relatively less documented in the literature, and more rigorous evidence of their success could inform future efforts. Research is needed to better understand how cities, including small- and medium-sized cities in LMICs, can structure water funds and other PES programs to maximize stakeholder support and benefits while avoiding challenges and pitfalls.

Blending funding sources for SWP and diversification

The case studies revealed information about which combination of funding sources and financing mechanisms were successfully used by cities for SWP and diversification, as well as success factors for accessing those funds and issues faced with certain mechanisms. LMIC cities do not yet have sufficient information about innovative or new financing mechanisms or funding sources available to them (such as the Green Climate Fund and green bonds). Additional research could further define barriers to access to funding sources and financing mechanisms, as well as roles played by governments and donors to increase CWA readiness to access additional funding sources and financing mechanisms.

4.4 FUTURE RESEARCH

This study identified evidence gaps around SWP and diversification for each of the three research questions. Many of these gaps centered around similar topics, including the lack of prioritization of planning for uncertainty and implementing measures to address risks to source water, the need for participatory engagement, and the importance of understanding and communicating trade-offs to stakeholders and decision-makers. In addition, much of the research available on this topic is from relatively larger cities or from high-income contexts. An overarching evidence gap remains as to how CWAs in small- and medium-sized cities in LMICs can plan, negotiate, and finance SWP and diversification measures. Given that the largest increase in urban population is expected to occur in small- and medium-sized cities, this is a particularly important area of study (UN-HABITAT 2020).

Future implementation research is needed to better understand how CWAs in LMICs can most effectively undertake planning, negotiation, and financing to implement SWP and diversification measures. A set of key questions that should be addressed by future work are shown in Table 11.

Table 11. Future research questions

Theme	Research Questions
Cross-cutting	What specific participatory processes for SWP or diversification are realistic and effective to implement in LMIC cities to promote equitable outcomes for marginalized groups such as youth and women in source water contributing areas? ● What do these processes cost to implement, and what are the benefits to the planning process?
Planning	How can CWAs be motivated to consider risks to urban water supply systems and resilience strategies in their planning efforts? ● How can planners in LMICs best assess and communicate uncertainty and risks to the stakeholders participating in the water planning process (or to decision-makers)? ● What methods to estimate and communicate the costs, benefits, and trade-offs of SWP and diversification solutions to stakeholders most effectively facilitate the decision-making process? ● How can CWAs guide the planning process to ally decision-makers and stakeholders in implementing just and equitable SWP and diversification investments/decisions?
	How can CWAs tailor existing tools and planning frameworks to effectively evaluate SWP and diversification options given limited data availability and technical capacity? ● How is the information produced used by decision-makers to improve project implementation and success? ● Does the planning exercise produce the information needed by the decision-makers in a timely and transparent form? ● If not, how can the tools best be tailored to based on needs?
Negotiation	How can incentive structures be set up in instances where finances are limited or when financial incentives may not be an option? ● How can incentive mechanisms be appropriately designed/ structured and implemented to mitigate potential market distortion? ● What potential risks are associated with these incentive structures, and what risk mitigation options are available?
Finance	How can a CWA effectively quantify the costs and benefits of SWP and diversification projects to justify investment?
	How can LMIC cities structure water funds and other PES programs to maximize stakeholder support and benefits while avoiding challenges and pitfalls?
	How can cities leverage climate funds, green bonds, and other new sources of finance to fill gaps in available finance?

APPENDIX A: DETAILED METHODOLOGY ON LITERATURE REVIEW AND CASE STUDY SELECTION

A.1 LITERATURE REVIEW APPROACH

The primary goal of the literature review was to analyze the existing body of knowledge regarding how city water authorities (CWAs) can improve the resilience of urban water supply systems through source water protection and diversification. The literature reviewed was a compilation of policy analyses, peer-reviewed journal articles, case studies, and other available publications identified through literature searches focused on urban water security and resilience, source water protection (SWP), and diversification measures in low- and middle-income countries. The search terms used included "urban water security," "source water protection," "source water diversification," "resilient urban water system," "urban water supply," and "diversified water portfolio," among others. We also included sources found from references of these selected publications. We also included sources shared by sector experts in our preliminary expert interviews. Although our literature review focused on SWP and diversification measures as potential avenues to catalyze urban water security, our review also explored some literature on topics such as water quality, watershed governance and transboundary water management, as well as gender equity and social inclusion in the water sector, specifically in urban contexts. These are all inherent components to consider gaining a holistic, in-depth understanding of resilient urban water security systems.

In total, our literature review included 171 references on topics related to the improvement of urban water supply systems through SWP and diversification. The literature included work from over 42 countries. We aimed to focus on recent publications, specifically published within the past decade; however, we included some older references dating back to the 1990s to provide context for modern SWP and diversification strategies in cities. The resources used included both gray and peer-reviewed literature, which represented a wide array of geographies and levels of scope (from city-level to national and international) (Figures A1 and A2). The city-level literature included in the review focused predominantly on cities in Latin America, Africa, and Southeast Asia. India, South Africa, Ethiopia, Kenya, Brazil, and Peru were discussed most in the reviewed literature. Approximately 103 of the references focused on case studies or analyses based on numerous countries, while approximately 37 pieces focused specifically on one city.

Figure A1. Number of references per region – excluding global

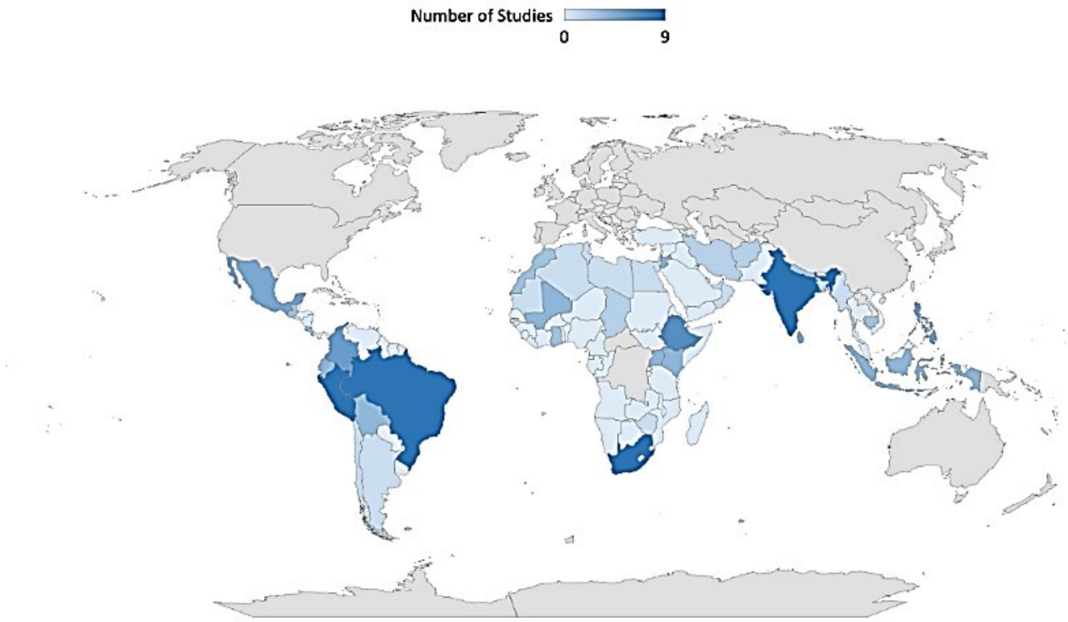
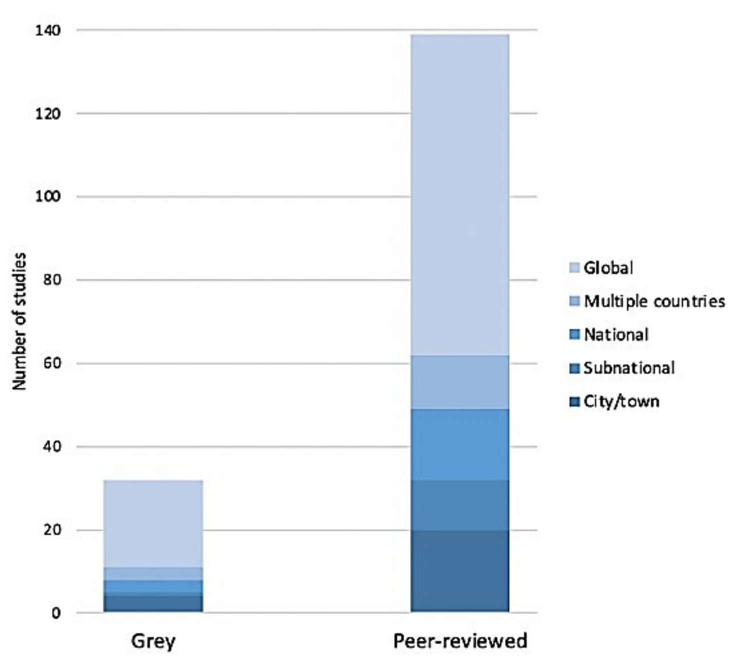


Figure A2. Number of references disaggregated by type and scale



An initial appraisal of the literature assisted in the development of the methodological framework, as well as in finalizing the research questions. **Informed by the methodological framework, we categorized the reviewed literature into three thematic components within the existing body of knowledge**:

1. Planning capacity challenges and enablers at the watershed level that comprise the ability of CWAs to monitor and assess the effects of biophysical uncertainties on water supplies.

2. Negotiation challenges and enablers to resilient urban water supply: challenges and enablers at the regulatory and policy level, for example, capacity limitations, sectoral conflict, etc.
3. Financing challenges and enablers to resilient urban water supply: challenges and enablers relating to CWA's ability to access long-term, sustainable financing for SWP and diversification projects and initiatives.

Analysis of the literature provided us with a set of preliminary evidence gaps, which served as a starting place regarding the elements to focus on within the comparative case study analyses. We identified lines of inquiry for further research based on a lack of literature or lack of detail within both gray and white literature that was reviewed in relation to testing the hypotheses.

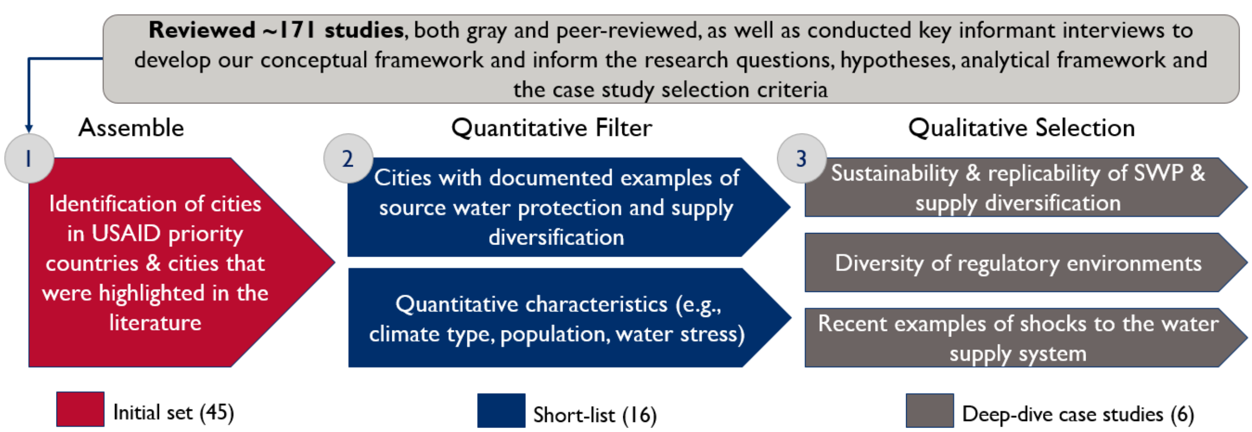
A.2 METHODOLOGY FOR COMPARATIVE CASE STUDY ANALYSES

Cities in low- and middle-income countries (LMICs) face a myriad of challenges in achieving urban water supply security. The goal of the deep-dive case studies was multifaceted, including the need to address outstanding evidence gaps from the literature review, further refine research questions within the framework, and find LMIC cities that are making headway toward resilience despite these challenges to understand how they overcame obstacles in ways that can inform future research and provide lessons that are replicable in other cities.

A.2.1 CRITERIA FOR CASE STUDY SELECTION

As noted in the research framework, a water security lens provides a more holistic approach to water resources management for making urban water supply more resilient. While CWAs are often one of many stakeholders ensuring water supply security for urban water users, they need to coordinate with watershed organizations and other actors to secure their water supply from surface and groundwater resources that are abstracted and transported to cities. To reframe the challenges defined above as pathways toward success, CWAs can work toward achieving urban water supply security goals using tools that can be separated into two key categories: sustainable management of source water by **diversifying water supplies** and the **protection of existing sources of water supply** as defined in the background. We identified seven cities for case studies using a filtering process described here (Figure A3). We analyzed the planning capacity, governance, and finance components of implementing the tools defined above at the city level, and a comparative synthesis was developed according to the research framework.

Figure A3. Method for selection of cities for case study deep dive



An initial literature review resulted in a list of 45 LMIC cities (Table A1) experiencing water supply security challenges, including cities in USAID priority countries. The criteria used for selecting the final set of case study cities started with a sub-selection of the 45 LMIC cities that have documented policies and actions contributing to increased water security and resilience, specifically in relation to existing and proposed SWP and water supply diversification solutions. To ensure a diversity of geographic, climatic, and demographic profiles among the final set of cities, we recorded a set of relevant characteristics for each of the 45 cities, including geographic region, Food and Agriculture Organization of the United Nations (FAO) global ecological zone (FAO 2012), metropolitan area population (Central Intelligence Agency 2022), national urban growth rate (World Bank 2020), national income level (World Bank 2022), national water stress (FAO 2018), and climate (e.g., mean annual temp, mean annual precipitation) (Bastin et al. 2019a). We ensured diversity in these characteristics by adding a selection of cities that filled gaps in any of the quantitative characteristics. If multiple cities from one country were represented, the city with the clearest case for examples of planning capacity, governance, and finance enablers that have improved implementation of tools to improve water supply resilience was chosen based on the literature reviewed.

Table A1. List of 45 cities considered for deep-dive analyses with 16 shortlisted cities shown bolded in red

Country	Cities
Africa	
Democratic Republic of Congo	Lubumbashi, Kinshasa
Ethiopia	**Addis Ababa**
Ghana	**Accra,** Tamale
Kenya	Bomet, **Nairobi,** Narok
Liberia	Monrovia
Madagascar	Antananarivo
Mali	Bamako
Mozambique	**Maputo**
Nigeria	Ibadan, Kano, Lagos
Rwanda	Kigali
Senegal	Dakar
South Africa	**Cape Town**
South Sudan	Juba
Tanzania	Arusha, Dar es Salaam, Mwanza, Tarime
Uganda	Kampala, Entebbe, Jinja
Zambia	**Lusaka**
Asia	
Cambodia	**Phnom Penh**
India	Chennai, **Delhi**, Mumbai
Indonesia	Jakarta
Myanmar	Yangon/Monywa
Nepal	Kathmandu
Philippines	**Manila**
Thailand	Bangkok
Central Asia	
Kazakhstan	Almaty
Latin America & Caribbean	
Bolivia	**La Paz**
Brazil	Rio de Janeiro, **São Paulo**

Country	Cities
Colombia	**Bogotá**
Ecuador	**Quito**
Guatemala	**Guatemala**
Haiti	Port-au-Prince
Peru	**Arequipa**
Middle East	
Egypt	Cairo
Jordan	**Amman**

This selection process resulted in 16 shortlisted cities with a minimum of three cities each from Africa, Asia, and Latin America, and one from the Middle East. These cities were selected to include all three country income levels (low, lower middle, and upper middle), eight of the 16 FAO global ecological zones, and populations from less than one million to more than 30 million with the primary consideration being documented instances of water supply diversification and source protection solutions. This diversity is illustrated with relation to the full set of 45 cities in Figure A4 and Figure A5.

Figure A4. Annual mean precipitation (millimeters [mm]), annual mean temperature (°Celsius [C]), and FAO global ecological zone for all cities evaluated, all extracted from WorldClim Version 2 (1970–2000) (Bastin et al. 2019a)

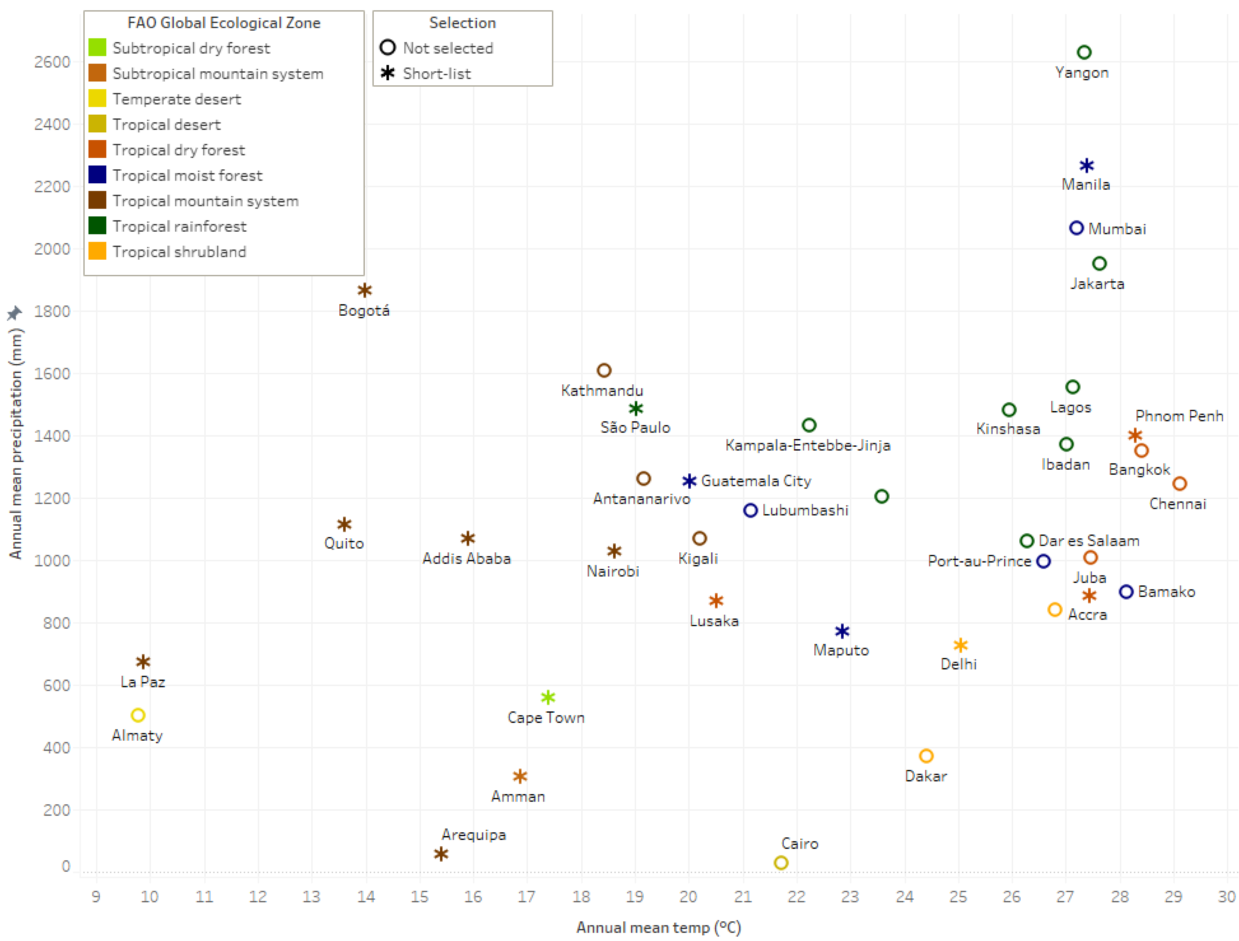
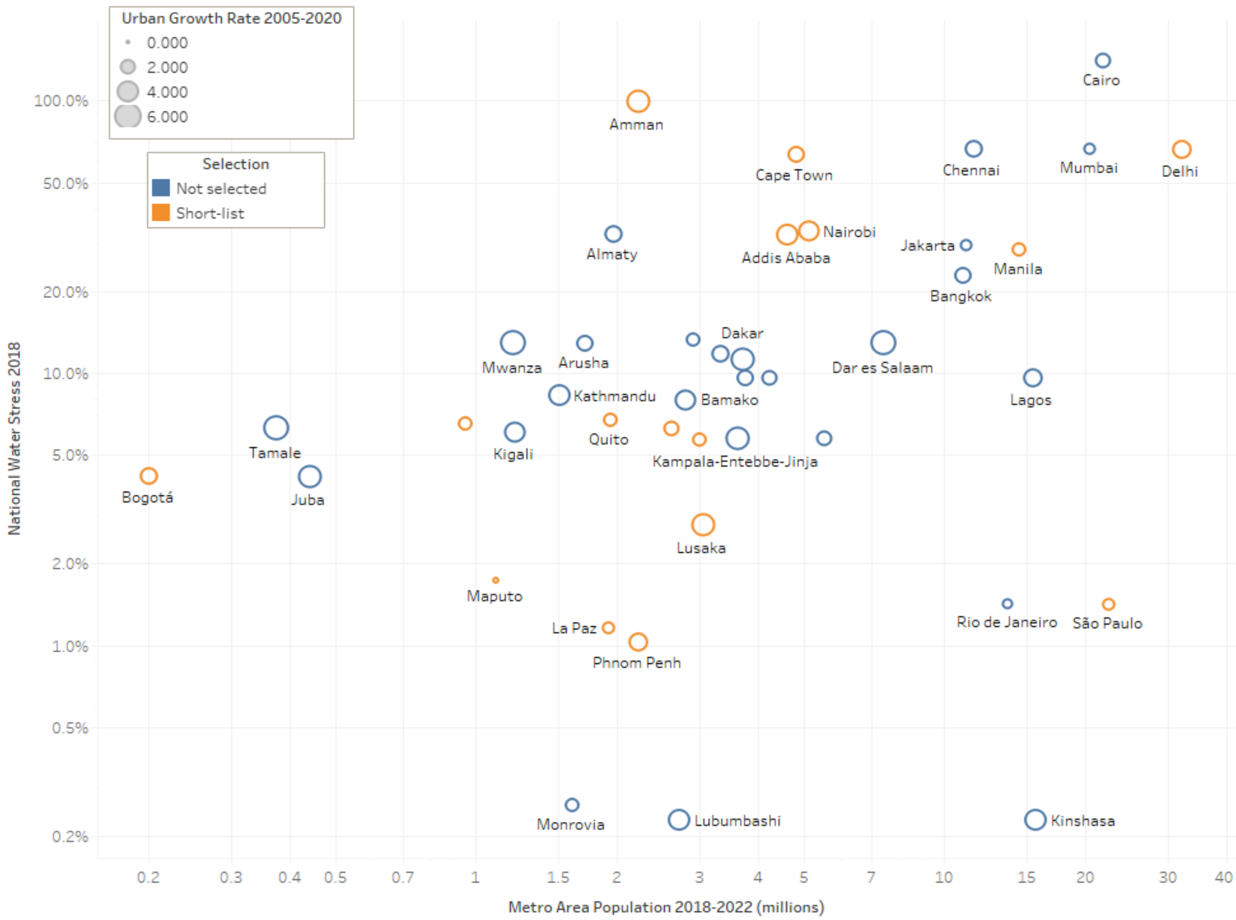


Figure A5. National water stress (percentage) from 2018, metropolitan area population (millions) from 2018–2022 depending on the source, and urban growth rate (percentage) averaged from 2005–2020 for all cities evaluated



*Shortlist cities shown in orange. All other cities shown in blue.

In addition to the quantitative factors shown in the previous figures, we developed a set of qualitative indicators to assess the degree to which SWP and water supply diversification efforts have been implemented (Table A2). First, the cities with weak examples of water supply diversification, meaning they are of small scale or limited description in the literature, are indicated as "unclear". We identified shocks for the shortlist cities from the last quarter of the twentieth century to present day from the literature, paying particular attention to climate related shocks. Additionally, a city was determined to have a population growth shock if it had experienced greater than 2% urban growth in the last 15 years (2005–2020) as noted in Table A2.

Table A2. Qualitative characteristics considered for selection of final case study candidates[25] with the final case studies shown in blue

Country	City	SWP	Diversification	Replicable	Sustainable	Shock
Ethiopia	Addis Ababa	✓	✓	✓	✓	Population

25 Summaries of the shortlist of case study candidates are provided in Appendix B.

Country	City	SWP	Diversification	Replicable	Sustainable	Shock
Ghana	Accra	✓	~	✓	⃠	Flooding
Kenya	Nairobi	✓	~	✓	✓	Population, Drought
Mozambique	Maputo	✓	✓	✓	~	Drought
South Africa	Cape Town	✓	✓	✓	✓	Drought, Population
Zambia	Lusaka	✓	✓	✓	✓	Population, water quality
Cambodia	Phnom Penh	✓	✓	⃠	✓	Flooding, Population
India	Delhi	✓	✓	⃠	⃠	Flooding, Population
Philippines	Manila	✓	✓	✓	✓	Shifting rainfall
Bolivia	La Paz	✓	✓	⃠	⃠	Glacier melt
Brazil	São Paulo	✓	✓	✓	✓	Drought
Colombia	Bogota	✓	~	✓	✓	Population
Ecuador	Quito	✓	✓	✓	✓	Drought, Volcanic Eruption
Guatemala	Guatemala	✓	✓	✓	⃠	Water quality
Peru	Arequipa	✓	✓	✓	⃠	Drought
Jordan	Amman	✓	✓	✓	✓	Population

✓ TRUE	⃠ FALSE	~ UNCLEAR

Another criterion for the selection of the case studies is a diverse set of global ecological zones. It is important to have representation of cities in mountain areas based on their unique vulnerability to shocks, including climate change and population growth. For example, water supply in mountainous locations is threatened by erosion, deforestation, and other ecological deterioration factors typical of high terrain (Buytaert and Bièvre 2012). Cities located in high elevation may be more susceptible to local changes in water supply because of their reduced catchment area and could have higher impacts from climate change in tropical mountain regions than lowlands. Cities located in lower elevations, even though they may be in drier areas, rely on water supplies from a greater upstream catchment area that includes many competing water users (Buytaert and Bièvre 2012).

We evaluated SWP and water supply diversification solutions implemented for replicability and sustainability, particularly in response to the shocks listed. Replicability indicates interventions with the potential to be implemented in other cities globally. Factors that affect replicability are relative ease of funding. For example, Phnom Penh was described as having large amounts of funding that has been easy to obtain, which is not true for most cities. Similarly, culturally specific examples of water cooperatives, as in the case of La Paz, may be difficult to replicate in other cases. Sustainability indicates interventions that can be sustained into the future based on availability of funds or acceptance among users. The implementation of solutions in pilot projects that may have limited staying power or that are difficult to scale are assumed to be of low sustainability. For example, the wastewater reuse best practices pilot in Accra has little information about the uptake results and plans for future funding or implementation. Similarly, reports and planning in Arequipa depend on the continued cooperation and success of mining companies in supplying future water supplies, which is uncertain and unclear. Thus, the seven cities chosen for the case studies are cities that demonstrated clear and robust SWP and water supply diversification solutions that are both replicable and sustainable.

A.2.2 CASE STUDY ANALYSIS AND SYNTHESIS

This study's approach for case study analysis focused on the steps taken, or not, to address the water security vulnerabilities created by specific risks, specifically biophysical, governance, and financial challenges. Each hypothesis was "tested" by looking at how CWAs achieved assessment, planning, and implementation of SWP and water supply diversification in the face of such risks. The degree of impact these SWP and diversification measures varied by case study and is expanded upon in the case study annexes. We collected data through targeted literature review for each city in combination with key informant interviews (KIIs). To respect the anonymity of these key informants, their identities are not disclosed in this report. The data collected via literature review and KIIs included basic background data, data on risk assessment, water planning, and financing mechanisms, as well as any lessons learned. We then conducted KIIs with experts from academia, government, and civil society to supplement outstanding data gaps from the literature review, thus the extent of questions posed to each KII in each examined city varies by deep-dive location (Table A3).

The final component of the case study analysis was the case study synthesis. The synthesis examined parallels and differences between the different components analyzed in each of the seven cities. First, we described the most prominent risks and challenges across the cities, distinguishing between biophysical, governance, and finance. Next, we identified common types of SWP and water supply diversification as well as water resource management tools and their enablers that have been implemented in the different cities. We highlighted both successful planning and implementation as well as challenges and the extent to which these challenges were shared by numerous case study cities. This synthesis illuminated patterns that allowed us to more easily assess whether themes existed according to region, climate type, etc. Finally, the team highlighted remaining evidence gaps across the case studies by evaluating the solutions according to our methodological framework. These remaining gaps and questions can serve as the basis for future work on this topic.

Table A3. Examples of topics examined for each case study city

Theme	Data Needed
Biophysical Context	Biophysical setting
	Population and growth rate
	Climate considerations (i.e., precipitation patterns, temperature)
	Watershed characteristics
	Climatic risks faced (i.e., drought, flooding)
Governance Context	Key actors and power dynamics
	Existence of water balance tool
	Engagement of stakeholders in informing baseline conditions
	Regulatory constraints
	Extent to which governance was considered in proposed solutions
	Existence of risk assessment and what risks were considered
	Existence of tradeoff analysis and what aspects are included
	Degree of stakeholder engagement and buy-in
	Whether stakeholders were informed about tradeoffs in terms they understood
	Method used for solution evaluation (i.e., policy options, infrastructure plans)
Financing Context	Method used to obtain financing and its level of sustainability
	Level of stakeholder buy-in and engagement in implementation
	Extent to which solution implementation was incremental
	Extent to which solution was adaptive

Theme	Data Needed
	Financial constraints
	Financing mechanisms considered/utilized

APPENDIX B: CASE STUDY SUMMARIES

ADDIS ABABA, ETHIOPIA

This case study investigated Addis Ababa, the capital of Ethiopia. The city has a total surface area of 520 square kilometers (km^2) and a population of approximately 4.6 million and is projected to grow to over 7.3 million people by 2030 (CIA 2022; CWRA 2021). As such, Addis Ababa is one of the fastest growing cities in the world, leading to many of its present challenges, including its efforts to establish a sustainable and resilient urban water supply system. Addis Ababa Water and Sewerage Authority (AAWSA), the city's water utility, only provides safely managed water through its piped network to less than 60% of the city's population, resulting in frequent water shortages, regular city-wide water rationing, and more than half of city residents regularly purchasing water from private vendors with higher prices (CWRA 2021).

Beyond rapid population growth, rampant and unregulated urbanization, and climate change, all of which are challenges experienced by most cities in LMICs, current challenges unique to Addis Abba and its water supply include:

- Demand exceeds supply: Currently the total water supply is approximately 542,000-580,000 cubic meters (m^3) per day, while the city demand is 1.1 million m^3 per day (CWRA 2021).
- One hundred percent of AAWSA's surface water sources are located outside the city boundaries: All of Addis' surface water sources are reservoirs located outside (20-30 kilometers [km]) the city's administrative boundaries. In addition to these important water supply infrastructures being located outside of the city's jurisdiction, they are extremely susceptible to the policies and actions in the upstream catchment, such as land use change from grasslands to agriculture.
- Potential for groundwater depletion: In the past five years, groundwater development has increased to meet more than half (60%) the city's supply (Birhanu et al. 2022). If current groundwater abstraction trends continue, groundwater levels could decline by more than 20 meters in some areas (Birhanu 2021). Actual extraction rates will remain unknown until groundwater monitoring and permitting improves.
- Deteriorating surface and groundwater quality: Addis Ababa is endowed with three major rivers, all of which are highly contaminated due to both point (industry effluent, urban wastewater discharges, etc.) and non-point pollution (sewage and agricultural runoff) (Assegide, Alamirew, Dile, et al. 2022). With approximately 65% of Ethiopia's industry located in Addis Ababa, poor enforcement of environmental regulations results in 90% of the city's factories, breweries, tanneries, etc. discharging their waste directly into nearby water bodies without proper treatment (Dessie et al. 2022). This is on top of the city's lack of adequate sanitation (sewer system connection coverage is 17% and even then AAWSA estimates it only has the capacity to properly dispose of 0.43% [1,727 m^3 per day] of the estimated 398,985 m^3 per day of wastewater produced by the population (Ministry of Water, Irrigation and Electricity 2020; CWRA 2022). There are concerns that these contaminants will infiltrate the groundwater.

In examining SWP and diversification measures for Addis Ababa taken by AAWSA and its partner institutions to date, the case study found activities using various methods to address increasing water demand and worsening water quality.

Increasing Water Supply through Infrastructure Investments

The focus on supply diversification began in the 1970s when the Legedadi Dam and the first phase of the dam's water treatment plant (WTP) with output capacity of 50,000 m^3 per day was commissioned. To date, the main components of the Addis Ababa water supply system are the Gefersa and Legedad Dams and their WTPs. After the construction of Legedadi, the Stage II Water Supply Project continued the water supply system expansion trend in the 1980s by increasing the capacity of the Legedadi WTP to 150,000 m^3 per day, increasing the total supply to about 180,000 m^3 per day in Addis Ababa, which was projected to meet demand up to 1992. Currently, the two systems (Legedadi and Gefersa) have a daily production of 150,000 m^3 per day, below the capacity of 180,000 m^3 per day. To close this gap, the development of Gerbi and Sibilu Rivers further north of the city have been under discussion since the 1990s, and the Stage III Water Supply Project (also in the 1990s) provided the emergency construction of two water supply projects: the Dire Dam and part of the Akaki well field. The current city administration is prioritizing resuming the delayed Gerbi and Sibilu reservoir projects (total 688,500 m^3 per day), which are projected to increase Addis Ababa city water demand coverage to 100%; however, this estimation does not take into account the AAWSA physical loss rate of 40% due to old water supply distribution networks (Birhanu et al. 2022).

Programs focused on borehole drilling and spring rehabilitation have also played a role in water supply improvement to noncentral parts of Addis Ababa. AAWSA is also encouraging institutions (both governmental and private) that have high water consumption rates to source their own water through boreholes, which will help address short-term supply needs, but is contributing to the city's uncontrolled drilling and abstraction and could lead to groundwater depletion (Birhanu et al. 2022).

Improving Water Quality through Infrastructure Investments

In addition to diversification of ground and surface water supply, Addis Ababa has also made significant investments in wastewater treatment facilities over the past four decades. The first wastewater treatment plant in the city (Kality Wastewater Treatment Plant) was completed in 1981, with a capacity of 7,600 m^3/day. It was designed to serve a population of 200,000; nearly 40 years later, only 13,000 people are connected to the system, with an additional 27,000-person equivalent demand coming from industrial and commercial connections (Wakejo et al. 2022). The Kality WTP was completed in 2018, with a capacity of 100,000 m^3 per day; however, the plant currently only operates at 40% of capacity due to different challenges of connecting the sewerage system of the city with the newly built sewerage network (Assegide, Alamirew, Bayabil et al. 2022). Past shortcomings of large wastewater treatment infrastructure could explain the recent trend for small, decentralized treatment plants, especially those developed to serve newly developed condominium houses, of which more than 600 decentralized sanitation facilities have been completed out of the planned 3,000 (Assegide, Alamirew, Dile et al. 2022; Thomas, Mammo, and Woldetsadik 2019).

Building Technical Capacity on Water Quality

Addis Ababa has also committed to providing technical assistance to industry players in their treatment of wastewater to decrease pollution in surrounding bodies of water (Federal Democratic Republic of Ethiopia 2016). This initiative is intended to directly impact water quality within the city limits, as well as downstream users. Between 2013–2018 AAWSA received support from five Dutch partners and the Ethiopian Public Health Institute to develop and implement its 2014 Climate-Resilient Water Safety Plan. Many of the activities focused on improving water quality management at the utility's laboratory and included staff capacity building and in-kind procurements (van den Berg et al. 2019). Under the Addis Ababa City Resilience Strategy (2020), the city is establishing an accredited environmental pollution monitoring lab and environmental data management system (CWRA 2022).

Strengthening WRM Governance

A large step toward water governance change was the Ethiopian Water Resources Management Proclamation No. 115/2005. This piece of legislation was one of the first to openly set protocols to protect water resources and surrounding ecosystems. The regulation laid out a permit system which stipulated pollution control measures via which offenders would have their permits revoked (Hailu, Tolossa, and Alemu 2018). The regulation did not, however, outline any fee for water use charges or release of waste into water sources. Regional and local governments were granted additional authority for monitoring compliance with the legislation, but this did not address the capacity gaps at these government levels, which inhibit their ability to monitor or institute additional viable measures for SWP.

To further ensure local stakeholder participation and autonomy in water resource management (WRM), the national government of Ethiopia instituted the River Basin High Councils and Authorities Proclamation No. 534/2007, which outlined a river basin planning approach and commitment to IWRM (Hailu, Tolossa, and Alemu 2018). Regional and city levels of government were given additional oversight responsibilities to ensure local needs were prioritized. The proclamation also acts as a blueprint for the establishment of river basin organizations and gives them the mandate to manage basin water resources. Addis Ababa falls under the purview of the Awash Basin Authority (AwBA), which was established before this law. Although these regulatory changes speak to the country's commitment to more equitable power frameworks, Addis Ababa requires capacity building for these changes to be effective in the city's ability to evaluate and implement viable water supply projects.

Evaluating Innovative Financing Mechanisms

One potential solution that Ethiopia is currently exploring is the introduction of PES schemes. Although PES schemes throughout the country have yet to be implemented, the country's government has conducted studies on the subject and is actively considering this option (ECOLINFA 2018). The city of Addis Ababa requested and received technical and financial support from The Nature Conservancy (TNC) to undertake relevant assessments for the potential of a water fund, which when established could be used to finance PES in the Awash River Basin (TNC 2019). Between 2020 and 2021, the Addis Water Fund Feasibility Project was undertaken, and this project conducted a feasibility study on establishing a water fund in the city (CWRA 2022). A decision on water fund implementation has not been made, but the city continues to prioritize diversifying funding sources, largely still through third-party donors such as development banks and NGOs, to ensure adequate consideration for green and gray investment trade-offs, stakeholder involvement, and adaptive solutions.

AMMAN, JORDAN

Jordan has one of the highest population growth rates in the world, which was been exacerbated by the Syrian refugee crisis, an ongoing issue spanning the last decade that has placed additional pressure on Jordan's water infrastructure systems and scarce water resources (Klassert et al. 2015; Marc François Müller et al. 2016). This case study focuses on Jordan's capital city Amman and its government-owned water utility, Miyahuna, which has a service area that spans approximately 13,000 km^2 and extends across Amman and the Zarqa, Madaba, and Balqa governates in Jordan. In total, the water supply system receives approximately 274,000 m^3 of water per day, but Miyahuna's website currently lists a much higher capacity of approximately 932,000 m^3 per day (Klassert et al. 2015; Miyahuna 2022). Currently, nearly 98% of Amman's households are connected to the piped network, though services provided along the piped network are often intermittent with wide disparities across regions of the city and low-income areas often receiving the most intermittent services (Klassert et al. 2015).

Beyond rapid population growth, rampant and unregulated urbanization, and climate change, all of which are challenges experienced by most cities in LMICs, current challenges unique to Amman and its water supply include:

- Transboundary competing demand for sources: Amman relies on two rivers as key sources of water – the Jordan and Yarmouk. Yet a large portion of the Jordan River's flow is diverted by Israel, and a large portion of the Yarmouk by Syria, Treaties specifically pertaining to water allocation exist between Jordan and Israel (1994 and 2021), Jordan and Syria (1953 and 1987), and Jordan and Saudi Arabia (2015), but they are difficult to monitor and enforce. For many years, the Yarmouk watershed has been exploited by Syria beyond levels stated on a bilateral agreement between Syria and Jordan, including construction of 21 dams upstream of Jordan's border (Marc François Müller et al. 2016). This also applies to groundwater. Jordan and Saudi Arabia hold a Disi Aquifer Pumping Agreement from 2015 that states neither country may drill extraction wells within a buffer zone between each country's extraction zones (Marc F. Müller, Müller-Itten, and Gorelick 2017). This agreement relies on a joint technical commission that enforces the outlined exclusion zones; however, the agreement does not limit annual groundwater abstraction for either country, and Saudi Arabia's extremely high levels of abstraction (>1000 million m^3 per year) pose a threat to Jordan's groundwater availability.
- Plans are dictated by international relations and fluctuating regional cooperation: Historically tumultuous relationships with neighboring countries regularly impact Jordan's current and future water security. Politics impact whether transboundary water agreements are upheld and if offers to buy water are accepted and transnational projects realized. For example, Jordan signed an agreement with Israel and Palestine in 2013 to implement the Red Sea–Dead Sea Conveyance to increase water supply to all three countries through seawater desalination. This project has mostly been abandoned due to a lack of commitment from stakeholders and broader political issues partially stemming from relations with Israel (Fanack Water 2022). More recently, as a result of the Abraham Accords, a water-energy deal between the United Arab Emirates, Jordan, and Israel was launched in 2021 and formalized in a memorandum of understanding at the Sharm el-Sheikh Climate Change Conference (COP27) (Robbin 2023).
- Stressed aquifers: Groundwater in Jordan is used twice as quickly as it can recharge (Klassert et al. 2018; USAID 2021c). Over 137,000 m^3 of water is pumped daily from the Jordan Valley to Amman. One source of water outside of the Jordan Valley is the Disi Water Conveyance Project, which carries water from the Disi Aquifer near the Saudi Arabia border. The aquifer is part of the Rum-Saq sandstone system, contains fossil water that is replenished at near-negligible rates, and is already showing substantial signs of depletion and increases in salinity (Marc F. Müller, Müller-Itten, and Gorelick 2017). While Amman itself draws approximately 274,000 m^3 per day from the Disi Aquifer (10% of the city's overall water supply), another nearly 220,000 m^3 per day is pumped for agriculture and provision of drinking water to cities in southern Jordan. The aquifer is projected to be exhausted as a resource by the end of the century. Illegal abstraction is common both within the agriculture sector and by illegal bulk water suppliers operating tanker trucks throughout Amman (KI Amman 2022). Except for a few academic studies, limited data is available to assess the extent of illegal groundwater abstraction and monitor the impact of illegal abstraction on aquifer levels.
- NRW: This is also a large challenge to Amman, including the lack of available, high-quality data on administrative and physical losses. Physical losses are estimated to reduce the total amount of water supplied to customers by approximately 25% with nearly another 25% estimated to be lost due to faulty meters and water theft from the system (Klassert et al. 2015). In 2014, the water utility's revenue was generated from less than half of the water supplied (46.8%) (Klassert et al. 2018). It is

estimated that financial loss for the Government of Jordan each year due to NRW is approximately $500 million (USAID 2019). This lack of data poses a risk to plans and ongoing projects to address NRW in Amman.

In examining SWP and diversification measures for Amman taken by Miyahuna and its partnering institutions to date, the case study found most activities focus on increasing and diversifying Amman's water supply with innovative technologies.

Increasing Water Supply through Diversified Infrastructure Investments

Jordan's Water Sector Capital Investment Plan highlights needed infrastructure investments in the country and timelines that run alongside population projections in an effort to manage the nation's extremely scarce water resources (Ministry of Water and Irrigation 2016b). Over a 10-year period, the plan aims to increase Jordan's supply capacity by 25–35% by prioritizing rehabilitation and maintenance to reduce leakage and improve existing infrastructure performance, developing new water resources to increase supply, and expanding wastewater service coverage across the nation. Alternative water sources continue to play an important part in Amman's water supply and the competing demands of agricultural and commercial water users.

Recycled water is a large part of Jordan's National Water Strategy and plans for future water sector development efforts. As of 2016, approximately 90% of Jordan's treated wastewater is reused for agricultural purposes, one of the highest rates of wastewater reuse in the world (Ministry of Water and Irrigation 2016a). Wastewater reuse has been an important component of Jordan's water sector strategies dating back to 1998. However, limited capacity of existing treatment plants needs to be addressed to further scale water reuse initiatives. It is estimated that by 2025 Jordan will have approximately 658,000 m^3 per day of treated wastewater that could be recycled and reused if associated risks are managed well. For example, agricultural productivity and soil response to treated wastewater must be monitored, managed, and institutionalized, and willingness to pay and participate within the agricultural sector must be accounted for in financial arrangements (Carr, Nortcliff, and Potter 2010; Saidan et al. 2020).

In addition to water supply from surface and groundwater sources and recycled water, desalination is another critical feature in Jordan's National Water Strategy (Ministry of Water and Irrigation 2016a). Desalinated water accounts for approximately 14% of Amman's supply, supplied primarily by the Zara-Ma'in Station (capacity of 110,000 m^3 per day). The plant was completed in 2006 and merged operations with Miyahuna in 2009 (Miyahuna 2022). The Zara Ma'in treatment plant recently underwent renovations funded by USAID (USAID 2021a)(USAID, 2021a). The development of infrastructure projects to increase desalinated water supply continue to be a priority. Following the abandonment of plans for the Red Sea–Dead Sea Conveyance, Jordan's Ministry of Water and Irrigation (MWI) is proceeding with a similar project within the country's borders with plans to desalinate water from the Gulf of Aqaba (Dead Sea), 333 km south of Amman. The plant will provide over 820,000 m^3 of water per day, pumped to the north of Jordan to serve cities such as Amman. Officials hope the plant will supply up to half of Amman's demand (approximately 685,000 m^3 per day) (Fanack Water, 2022).

Addressing Demand Management

Residential demand in 2020 for Miyahuna's customers is approximately 54 liters per capita per day (Ministry of Water and Irrigation, 2020). Amman, and Jordan in general, is known for having one of the lowest urban residential water demands in the world, particularly for a middle-income country. Water demand management has been a key strategy for MWI since the early 2000s and culminating in its inclusion in the 2004 Jordanian National Water Master Plan. A 2019 study of Jordanian government documents and interviews found that MWI's water awareness campaigns use two strategies to shape water users' behavior: (1) state insecurity (focuses messaging on the user's national responsibility for the nation's water network), and (2) citizen security (focuses messaging on how the user's wasteful daily water practices, can exacerbate water scarcity and therein jeopardize their own future water access) (Benedict and Hussein 2019). However, a 2018 survey of Jordanians' knowledge, attitudes, and practices regarding water by the USAID-funded Water Management Initiative project (WMI) found that while most residents were aware of the Jordan's water challenges, 40% did not believe that their country was facing a crisis (USAID 2020). WMI proceeded to support the government to conduct an awareness social media campaign in 2019 that resulted in people's knowledge of Jordan's water crisis increasing to 79%.

CAPE TOWN, SOUTH AFRICA

One of South Africa's capitals, Cape Town extends over 2,487 km^2 and was home to approximately 4.6 million inhabitants in 2020, of which approximately 1 million (18% of the urban population) live in sprawling informal settlements (Rodina 2019; Western Cape Government 2020). The Water and Sanitation Department of the City of Cape Town acts as the water service provider for the city and Drakenstein and Stellenbosch municipalities. It oversees providing water (including bulk water) and sanitation services, as well as managing water catchment areas and water storage.

Cape Town, like most cities in LMICs, is experiencing dwindling water supply in its source watersheds, worsened by climate change. Current challenges unique to Cape Town and its water supply include:

- Undiversified water supply: Cape Town depends almost entirely on the Western Cape Water Supply System (WCWSS), a raw surface water-storage system (capacity of 900 million cubic meters [MCM]), of which six major dams constructed between 1920 and 2006 comprise 99.6% of the system's total capacity (City of Cape Town 2020). During a non-drought year, the city of Cape Town uses around 64% of the WCWSS available stored water, agriculture uses 29%, and smaller towns use around 7% (OECD, 2021).
- Rampant growth of invasive alien plant species reducing the WCWSS' water yield: Proliferation of invasive plants (e.g., pine and eucalyptus) in the basin will reduce the amount of water that reaches the rivers and dams by an estimated 55 MCM per year (OECD 2021). This equates to a reduction in the WCWSS yield of approximately 26.5 MCM per year, which if left unmanaged could up to an estimated 85 MCM per year by 2045 (City of Cape Town 2022a). This challenge also impacts groundwater availability; an analysis done by the Greater Cape Town Water Fund estimates that 1.8 MCM of groundwater in the Atlantis Aquifer is lost annually due to invasive alien plants (Stafford et al. 2018).
- Lack of coordination between water actors at different levels: In 2014, one year prior to a major drought, the national government was advised to limit water allocation for agriculture in the Western Cape to 173.6 MCM per year; however, in 2015, the national Department of Water and Sanitation decided to allocate 42.6 MCM per year above the advised quantity (Morabito 2018). This resulted in an overdraw of the WCWSS which effectively was equal to the "safety net" allocated to Cape Town, putting the city in an extremely vulnerable position, and likely contributing largely to the 2015–2018 water crisis, referred to as "Day Zero" (an allusion to the day the reservoirs would be empty).
- Groundwater quality: Agricultural activities, waste disposal, and poor waste infrastructure continue to pollute the aquifers in some areas of Cape Town and pose risks to the future viability of these water sources.

In response to the historical water stress and numerous water crises it has experienced, Cape Town, its Water and Sanitation Department, and partnering institutions, have implemented several SWP and supply diversification measures.

Augmenting and Diversifying Water Supply

The 2020 Cape Town Water Strategy outlines the city's commitment to diversified and incremental implementation of water source development and protection projects and approaches laid out over multi-year timeframes. Cape Town has committed to increasing its water supply by building affordable new capacity of approximately 300 million liters per day (MLD) over the next ten years in a way that is adaptable and robust to changes in circumstances. It will do so by investing about Rand (R) 4.7 billion (~$237 million) into developing groundwater sources that will bring approximately 105 MLD of groundwater online by 2036 (City of Cape Town 2022b). As of 2019, Cape Town used 12 MLD of groundwater (a little over 2% of the city's total water demand) (Olivier and Xu 2019). Two of the three groundwater projects, the Cape Flats Aquifer Management Scheme and the Atlantis Water Resource Management Scheme, include Managed Aquifer Recharge components, which is a technique that has been used in Cape Town since the 1980s. Finally, the city will develop additional water reuse and desalination facilities to be developed alongside and integrated with the existing surface water system. This diversification and increase in capacity are planned to continue beyond these initial ten years in suitable increments based on new climate data as it becomes available (City of Cape Town 2020).

Targeting Demand Management

To address demand challenges, Cape Town developed a Water Conservation and Water Demand Management Strategy in 2001, and it was subsequently updated it in 2007, 2010, 2012, 2013, 2014, and 2015 (City of Cape Town 2020). Through this strategy and its associated programs, Cape Town has instituted a thorough set of measures which outline water allocation limits per user based on the level of water stress experienced at a given time – a measure rooted in a thorough vulnerability assessment which utilized existing economic and climatic data for the region (Rodina 2019). The enforcement of consumer payment increases for high water use rates ensures that users are incentivized to decrease water use and thus minimize excess burden on water supply as a result of population growth and inconsistent rainfall. From 2015 to 2017, Cape Town's water use was reduced by over 40%, all while its population and economy continued to grow. However, numerous studies in the aftermath of Day Zero found that the price mechanisms used were considered to be ineffective, while non-price mechanisms were seen as having more impact on encouraging water conservation behavior (Booysen, Visser, and Burger 2019; Matikinca, Ziervogel, and Enqvist 2020).

Other demand focused measures were put into place during "Day Zero". Farmers from the Overberg region of the Western Cape made a one-time donation of 10 million cubic liters (0.01 MCM) of water in 2018 to the Western Cape Water Supply region (Rodina 2019). This allowed the city additional time to implement other solutions and was critical to the city's ability to avoid Day Zero. Short-term city-wide water use restrictions and supplemental water shared from nearby sources helped to mitigate the immediate effects of the drought. Cape Town also implemented an intensive water pressure control, leak detection, and repair program, as well as a rising block tariff system in an effort to address leakage occurrence (Matthews 2021).

Establishing a Water Fund

Launched in November 2018, the Greater Cape Town Water Fund is Africa's second water fund, and it is currently continuing efforts to raise funds and leverage investments to ensure the fund is sustainable long-term and can be used to finance future SWP efforts such as the mitigation of alien plant invasion which currently affects two-thirds of the sub-catchments that supply water to the WCWSS (TNC, 2022).

LUSAKA, ZAMBIA

Lusaka is the capital city of Zambia and one of the fastest growing cities in the world with an urban growth rate of 4.8% (Bastin et al. 2019a), expected to reach 4.7 million people by 2030 (from 3.4 million in 2021) (Phiri 2022). Lusaka Province, which includes the City of Lusaka, receives water supply and sanitation services from the Lusaka Water Supply and Sanitation Company (LWSC). In 2022, LWSC's water and sanitation coverage were 92.5% and 79.9% respectively (NWASCO 2023) Formed in 1988, ownership of LWSC is split amongst all districts in the province, with Lusaka City Council owning the largest share.

On top of rapid population growth and rampant and unregulated urbanization, the City of Lusaka and the Kafue River Basin, within which Lusaka is located, are experiencing key challenges to the water supply, which are expected to be exacerbated by climate change. These challenges include:

- Current water demands exceed the city's water supply: In 2020, LWSC had a current daily water supply capacity of 250,000 m^3 and its customers had a demand of 420,000 m^3 per day, leaving a deficit of 170,000 m^3 per day (40%) of demands. (LWSC 2020a).
- High NRW: This deficit does not take into account LWSC's NRW level of 47%, which means that nearly half of water treated and distributed by LWSC is never billed either due to physical losses, like leakages, or commercial losses, such as illegal connections, unbilled customers, and wastage on un-metered customers' premises (NWASCO 2021). The city's reliance on aging water infrastructure from the 1960s and 1970s contributes to leakage. This combined with the lack of investments in new water-related infrastructure, has exacerbated the shortfall in water supply (MCC 2020b).
- Overreliance on groundwater: Approximately 58-70% of Lusaka province's formal and informal water demands are met by groundwater (FRACTAL 2019). Due to the city's heavy reliance on groundwater for urban supply, groundwater resources are under stress from over abstraction and contamination from human activities (Chande and Mayo 2019; Reaver et al. 2020). In October 2022, Zambia's Water Resources and Management Authority (WARMA) reported that groundwater levels in Lusaka West are falling at alarming rates: where once accessible at 35-40 meters below ground, the groundwater table is now as low as 120 meters (WARMA 2022a, 2022b).
- Deteriorating water quality: Due largely to the physical characteristics of the aquifer, a third of the city's area is classified as having high or extreme vulnerability to groundwater pollution (De Waele et al. 2004; Kappauf et al. 2018; Nick et al. 2019). This makes groundwater especially susceptible to sewage contamination from unconfined waste pits, pit latrines, and poorly managed septic tanks in a city where only 18% of the province's population is connected to sewer networks and 83% of waste goes untreated (Kappauf et al. 2018; LWSC 2018). Widespread contamination of Lusaka's groundwater with bacteria, nitrates, ammonium from pollutants entering the aquifer has been a continuous problem for the city resulting in numerous outbreaks of cholera and other health issues like severe diarrhea (Adelana et al. 2008; Chande and Mayo 2019).
- Frequent power outages affect water supply: Lusaka's electricity supply relies on hydropower, which is subject to seasonal variability, causing low hydropower availability and rolling blackouts during the dry season (MCC 2020b; WWF Zambia 2018). However, climate projections suggest that this situation will worsen as rainfall patterns change and more dry periods occur (WWF Zambia 2018). Many commercial utilities, including LWSC, also limit the hours of water availability in order to save on high electricity costs (NWASCO 2021). As a result, the city averages 18 hours of water service

per day, but some neighborhoods have as little as 4 hours of service daily, while others have continuous 24-hour service (MCC 2020a).

In examining SWP and diversification measures taken by LWSC and its partnering institutions to date for Lusaka, the case study found activities using various methods to better coordinate on addressing endemic issues.

Improving Institutional Stakeholder Coordination on Water Security

Officially started in 2016, with origins dating back to 2012, the Lusaka Water Security Initiative (LuWSI) was formed to coordinate various stakeholders working towards groundwater pollution prevention, sustainable groundwater exploitation and improved access to water supply and sanitation in Lusaka (LuWSI 2018). It has grown into a robust multistakeholder platform in Lusaka convening stakeholders from 33 different organizations from the public sector, international donors, private sector and civil society actors to facilitate dialogue, planning, coordination, and collaboration on water sector issues within an urban and peri-urban context (LuWSI 2021).

Expanding Groundwater Knowledge and Improving Its Management

Since 2005, WARMA and the government of Zambia have been receiving technical support from the Federal Institute for Geosciences and Natural Resources (BGR) through various projects: *Groundwater Information System and Management Programme for Lusaka* (2005-2009), *Groundwater Resources Management Support Programme (GReSP)* (2009-2015), and GReSP II (2000-2024) (BGR 2021; 2019). Earlier projects focused on performing extensive assessments and analyses of Lusaka's groundwater system and supporting appropriate safeguards for drilling new wells in the Zambian Water Resources Management Act of 2011. Recent efforts have focused on strengthening the technical capacity of WARMA and LWSC and its related Catchment and Sub-catchment Councils in sustainable groundwater management (BGR 2021).

GIZ is funding two LWSC-led groundwater protection initiatives: the Wellfields Protection Project and the Lusaka West Water Supply Project (LuWSI 2021). Both aim to protect groundwater by securing land tenure to protect wellfield sites from encroachment, improving sanitation and solid waste management, increasing groundwater monitoring, delineating and gazetting groundwater protection zones, and tightening Lusaka City Council's role in approving plans and enforcing construction standards (LuWSI 2022b). There is also consideration of exploring new wellheads outside Lusaka for meeting water demands (LuWSI 2022a). However, it is unclear whether the quantity of groundwater is sufficient to meet future demands given climate change and increasing rates of abstraction.

Reducing External Risk and Diversifying Water Sources

Between 2006 and 2012, Lusaka partnered with the World Bank in the Water Sector Performance Improvement Project. This included the rehabilitation of Iolanda Water Treatment Plant and downstream pumping stations, borehole rehabilitation and development, and rehabilitation of sewer treatment and collection systems. Future plans expect an increase in water supply to Lusaka Province by an additional 450,000 m^3 per day by 2035 (LuWSI 2022a). Given hydrological studies revealing the limits of Lusaka's groundwater resource, the city's diversification strategy focuses on the Kafue River to supplement this additional water supply. Some examples of projects include:

- New Lusaka Bulk Water Supply Project, valued at approximately $190 million (status: pre-feasibility; funders: JICA and AfDB; objectives: construct a new water intake and treatment plant at Kafue River, a distribution main, and reservoirs) and
- Kafue Bulk Water Supply Project, valued at $150 million (status: active; funder: Exim Bank of China; objectives: construct 150,000 m^3 per day intake structure, build a new raw watermain

from intake to the treatment plant and from treatment plan to Lusaka, upgrade the plant capacity by 50,000 m^3 per day, and rehabilitate the booster station in Chilanga (LWSC 2020a; 2020b).

There are also plans in place to build solar capacity to increase grid resiliency and reduce the number of power outages that disrupt water systems as well as to install solar water pumps for groundwater abstraction (Mwape 2019).

MANILA, PHILIPPINES

This case study examined Metropolitan Manila (Metro Manila), also referred to as the National Capital Region, which as the capital of the Philippines, encompasses an area of 619.54 km^2 and houses a total population of 13.5 million people or 12% of the national population in 2020 (PSA 2021). Since the privatization of Metro Manila's water supply services in 1997, the regulatory agency (Metropolitan Waterworks and Sewerage System [MWSS]) has been responsible for sourcing the city's raw water and developing new water sources. MWSS supplies a contractually obligated water allocation to each of the two private utilities (Manila Water Company, Inc. and Maynilad Water Services, Inc.), also referred to as concessionaires, and monitors their performance against their contracts. The concessionaires store, treat, and distribute the water to the customers in their designated service areas through systems maintained by the concessionaire. They also manage sewerage for the city.

Current challenges to Metro Manila's water supply are similar to other cities located in LMICs: population growth, rapid urbanization, land use change in the watersheds where the city sources its raw water, and climate change. The city's geographic location also makes it vulnerable to disasters like earthquakes or volcanic eruption. Challenges unique to Metro Manila include:

- Insufficient water supply to meet city's demands: Since privatization, the number of water service connections in the service area has increased by 190%; however, despite plans, no new water sources have been added to the supply to meet the augmented demand during this same time (Torio, Mendoza, and Torres 2021). Metro Manila water demands are projected to continue exceeding its supply until 2026 (Ty 2022).
- Lack of diverse sources make water supply vulnerable: Nearly 90% of the city's water supply is sourced from the Umiray-Angat-Ipo rivers system, located 58 km northeast of the city and covering multiple watersheds and local government units (LGUs).
- Water sources closer to the city are degraded: A recent study found that domestic wastewater discharges to Laguna Lake account for 30% of the pollution load, while industrial and agricultural discharges account for 30% and 40%, respectively (MWSI 2022).
- Land subsidence due to groundwater abstraction: Rapid urbanization and lax regulation led to unsustainable groundwater extraction rates that quadrupled starting in the 1970s, which have resulted in significant land subsidence, lowering of the water table, and saline intrusion across Metro Manila (Siriwardane-de Zoysa et al. 2021).
- Too many uncoordinated actors: At least 32 government institutions and 3,576 LGUs have redundant responsibilities related to water, insufficient coordination, lack of engagement and transparency with the public, and fragmented water policies.

In examining the SWP and diversification measures taken to date to improve Metro Manila's water security, the case study identified activities concerning groundwater protection, watershed restoration, development of smaller local surface water sources, establishment of a new government agency to oversee water resources management, and innovative financing mechanisms.

Restricting groundwater use

Studies in the early 2000s established a clear relationship between groundwater over extraction and land subsidence in Metro Manila. Four areas of concern (with clear cones of depression[26]) were identified in Metro Manila and four areas in neighboring Cavite and Bulacan Provinces (NWRB 2004). In response to this crisis, the National Water Resources Board (NWRB) (in charge of groundwater permitting) put in place legislation in 2004 to stop the construction of deep wells in the city (except for in emergencies). The legislation began a decade-long campaign to crackdown on illegal well operation. It also established monitoring sites near the cones of depression, which feed data into the Groundwater Management Plan (GMP) Dashboard and informed the creation of the 2017 GMP for Metro Manila (NWRB 2021). A recent study found that these source protection measures may finally be paying off as land subsidence has slowed from an average of 3 centimeters (cm) per year (between 2003–2010) to 2 cm per year (between 2015–2020) (Smith 2022).

While current groundwater sources make up a little over 1% of the total raw water supplied to the MWSS service area by concessionaires, MWSS and its concessionaires still rely on groundwater in their planning and consider it their primary line of defense in the event of an emergency. In response to the 2019 water crisis, during which a two-year drought culminated in MWSS being unable to provide the full allocation to the concessionaires, approximately 52,000 households within the East Zone of Metro Manila lost water service for a week, and hundreds of thousands more had only intermittent service, Manila Water Company, Inc. increased their raw groundwater abstraction by 637% (Lee et al. 2020; Manila Water Company Inc. 2019, 2022a). Both concessionaires continue to invest heavily in developing more groundwater sources to use in case a similar emergency should arise.

A watershed restoration flagship project

The Annual Million Tree Challenge (AMTC) took place from 2017 to 2021 in the seven critical watersheds from which Metro Manila obtains raw water. During this period, MWSS partnered with the concessionaires, ministries, LGUs, private corporations, and NGOs to plant 5,212,344 seedlings reforesting 12,486 ha (MWSS-CO 2022a). Since its conclusion, AMTC has formed an NGO called the Million Trees Foundation Inc. (MTFI) with the objectives of scaling up its results using an ecosystem-based approach to plant 10 million more trees by 2030 based on the knowledge accumulated over the past five years (KI Manila 2022a). One of MTFI's first projects has been the co-development of a watershed restoration roadmap (2022–2030) with MWSS to outline how MWSS and its partner agencies will collaborate to achieve short- and long-term goals (Talavera 2022).

Developing smaller water sources

Developed in 2011 and regularly updated, the Water Security Infrastructure Roadmap (2016-2037) is MWSS's primary guiding document for the development of a sustainable and resilient water supply within Metro Manila and parts of Rizal, Cavite, and Bulacan provinces for the next 25–50 years (MWSS-CO 2022b). The most recent iteration of the roadmap differs from years past in that it has many more small-sized (<50 million liters per day [MLD]), short- to medium-term (<3 years), and multi-phased

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26 Pumping groundwater from a well in an unconfined aquifer (water table), like those found in Metro Manila, lowers the water table near the well in the shape of an inverted cone. The size (how far it extends) and shape (slope) of the cone of depression depends on the pumping rate and physical characteristics of the aquifer (e.g., geology, water storage). As the cone of depression grows, it can decrease water pressure and modify the direction of groundwater flow and distribution of pollutants within the area of influence around the well and, worst-case scenario, lower the water table below the bottom of the well.

projects that will incrementally bring new water sources online, as opposed to prior plans that proposed fewer projects, all with much longer timeframes (10+ years) and larger supply increases (300+ MLD). Meanwhile, each concessionaire has a Capital Expenditure Plan that outlines how capital expenditure will be used to rehabilitate facilities inherited from MWSS or design and build new projects to meet the service obligations under the Revised Concession Agreement. Both concessionaires are developing and using Modular Treatment Plants (ModTPs) to supplement the raw water supply provided by regulator (MWSS) by drawing and treating raw water from the nearby rivers and streams. 30 MLD, or less than 0.75%, of the city's total water supply, is now sourced through ModTPs.

Addressing water resources institutional fragmentation

Legally, NWRB, which was established by Presidential Decree 424 in 1974 (renamed in Executive Order 1987-124-A), should be the lead agency responsible for coordinating and regulating all activities related to water resources management (Tabios 2020). Presidential Decree 1067 (Water Code of the Philippines [1976]) further defines NWRB's responsibilities by putting it in charge of the control and regulation of the utilization, exploitation, development, conservation, and protection of water resources (Hall, Pulhin, and Rola 2018). However, in practice, there has never been the political will or associated funding required for NWRB to assume all the responsibilities with which it was legally endowed. Since 2012, politicians have been trying to address this issue by introducing legislation proposing the creation of a Department of Water Resources. Resubmitted in 2022, the outlook is more optimistic now that the creation of the Department of Water Resources is an output of the approved 2021 Philippine Water Supply and Sanitation Master Plan and has the support of President Marcos (Bordey 2022).

Cutting-edge financial mechanisms

Several innovative financial mechanisms have been used to fund source water protection and water supply diversification measures in the Philippines. Since 1997, the Laguna Lake Development Authority has been enforcing an environment user fee system to deter polluters. More investigation is needed to determine the efficacy of this "polluter pays" mechanism, how the proceeds are spent, and if they should be scaled up. The country's growing bond market is being harnessed to finance SWP and diversification; at least four green bonds have been issued that have allocated use of proceeds to water projects, and the Manila Water Company Inc. issued a $500M sustainability bond to fund water infrastructure in 2020 (Climate Bonds Initiative 2020).

QUITO, ECUADOR

The Metropolitan District of Quito (DMQ [*Distrito Metropolitano de Quito*]) is the capital of Ecuador, an upper middle-income country with a population of nearly 2.7 million, which faces a host of challenges to its water system. The water utility *Empresa Pública Metropolitana de Agua Potable y Saneamiento de Quito* (EPMAPS) is a government agency operating under municipal legislation. In 2020, drinking water and sewerage coverage in DMQ was 98.8% and 94.1%, respectively (EPMAPS 2021).

Beyond rapid population growth, catastrophic events (i.e., volcanic eruptions and telluric events), and climate change, all of which are challenges experienced by most LMIC cities, current challenges unique to DMQ and its water supply include:

- Dependence on distant surface water: 97% of water supplied by EPMAPS comes from over 50 intakes from high-elevation rivers and reservoirs located up to 100 km away. Given the large distances that the raw water must travel to reach the DMQ, the conveyance system is particularly vulnerable to potential shocks related to both natural events and system failures (SEI 2021).

- Land use change in the watersheds where the city sources its raw water: There have been significant changes in land use in the upstream as more areas are occupied for pastures, vegetable crops, and pine and cypress plantations and gravel mining operations expand (Lascano 2018). Protecting these distant yet important watersheds is challenging, especially from detrimental local land management practices, like using controlled to clear land for agriculture.
- Environmental flows: Ecological flow requirements legally protected, but not enforced.

In response to these challenges, decision-makers have taken a forward-looking, ambitious approach towards anticipating future water needs, providing stewardship of watersheds, and developing and executing plans to prepare for future risks to sustainable water supplies for the DMQ. The case study identified several key SWP and diversification measures taken to improve Quito's water security, such as constructing new infrastructure, creating a water fund, establishing a permanent risk management unit within EPMAPS, and NRW reduction measures.

Establishing a Water Fund

From the 1960s to the early 1990s, EPMAPS focused on infrastructure construction and developing new sources to address the supply gap and prepare for population growth projections. In the late 1990's, EPMAPS also started to work towards addressing water resource risks related to land use changes and watershed protection by convening key local stakeholders that relied on the same water sources to create a shared space to identify and quantify the risks and to jointly explore management options. Building on this work, the municipality of Quito, with the support of The Nature Conservancy (TNC), created a private trust fund known as the Fund for the Protection of Water (FONAG [*Fondo para la protección del Agua*]), the world's first Water Fund. Setting up FONAG required an understanding of policy and regulatory frameworks, strong leadership, stakeholder perspectives, negotiation, and patience, as it took three years from its initial conception in 1997 to its formation in 2000.

FONAG is responsible for the protection and conservation of the Upper Guayallabamba, Antisana, Oyacachi, and Papallacta River Basins, which are essential for preserving the water supply to the DMQ and its surrounding region (Kauffman 2014). The operational area of FONAG is approximately 5,025 square kilometers (Lascano 2018). It contracts with local partners to implement conservation, restoration, and education programs (TNC 2023a).

The FONAG fund has grown over time due to its sustained income, secured through municipal ordinances of 2% of EPMAPS' annual budget (phased in from 1% to 2% over a period of four years) and annual commitments totaling $51,000 per year of contributions from the Quito Electrical Company and local beverage companies. A financial management decision was made early on to limit annual spending to only yields from interest and investments, this allowed the fund to grow while it built its scope of work incrementally over time. By the end of 2018, FONAG's estate had grown to $18.7 million, generating an annual budget between returns on investments and proceeds from these agreements of $2 million per year (Coronel T. 2019).

Increasing Monitoring

FONAG places a strong priority on monitoring the impact of its activities and results. It collaborates closely with EPMAPS to better leverage funds to invest in regional water and soil monitoring programs, which it uses to analyze the impacts of its nature-based solutions initiatives and better target areas for improvement, which allow the fund to demonstrate effectiveness and seek additional investments (Ertel et al. 2019). A recent study conducted by the University of San Francisco, Quito, compared water quality values from 2019 as compared to 2014 and 2016 and determined that areas that FONAG supported with restored vegetative cover and reduced bovine activities had improved water quality, finding lower levels of phosphorus, BOD and fecal coliforms (ECAP 2021).

Adopting a Risk-Based Utility Management Approach

Since its creation in 1960, EPMAPS has gradually adopted an increasingly comprehensive and diversified risk preparedness approach that takes into consideration a range of climate, geological and ecological risks. Some speculate that this new era began in 2011 with the creation of the Risk Management Unit. Also launched in 2011, are three key EPMAPS programs that apply a systems-thinking approach to current challenges like demand-side management (*Consumo Responsable del Agua* [CREA]), NRW (*Programa de Reducción de Agua no Contabilizada*), and water quality and city river health (*Descontaminación de ríos y quebradas del DMQ*) (EPMAPS 2012; FONAG 2018).

SÃO PAULO, BRAZIL

The Metropolitan Region of São Paulo (RMSP [*Região Metropolitana de São Paulo]*) is a massive metropolitan area with 22.43 million inhabitants with a total area of 8,051 km^2, giving it a density of 2,786 people per km^2 (CIA 2022; EMTU 2022). Water is generally provided to households by the State Water and Sanitation Company of São Paulo (Sabesp), a mixed capital company with a majority stake by the State of São Paulo, which provides water and wastewater services to municipalities throughout the entire state of São Paulo, serving a total of 27.9 million inhabitants (Pena 2011; SEC 2018). In the RMSP, Sabesp served 21.8 million people in 2020 (93.1%) (ANA 2022). As of 2020, Sabesp retails water directly to consumers in all except two municipalities in the RMSP, São Caetano and Mogi das Cruzes, to which it provides wholesale water who then resell to customers (Sabesp 2020b).

São Paulo, like most cities in LMICs, is experiencing rapid deforestation and urbanization of upstream watersheds that supply it with water. Climate change is compounding these challenges. Current challenges unique to the RMSP and its water supply include:

- Dependence on a system ill-designed for current conditions: Built in the 1970s, the Cantareira System is the largest of eight water supply systems, all of which are located outside the RMSP, that feed the City of São Paulo. Operated by Sabesp, it provides 47% of the total water supply used by the RMSP (Sabesp n.d.; Cho et al. 2023). During the 2013–2015 drought, its six main reservoirs reached below 5% of their 1.3 billion m^3 capacity, resulting in their failure and a water crisis that caused a total economic loss of BRL 1.6 billion (~$318 million) for the industrial (67% of total loss) and water sectors (33% of total loss) serviced by the Cantareira System (Ciasca et al. 2023).
- Upstream land use and land cover change: The River basins that supply RMSP's raw water are experiencing increased deforestation, mainly from agriculture and urbanization (Paiva et al. 2020; Richards et al. 2015). These land use changes pose challenges of increased sediment loads and anthropogenic contaminants, and changes in precipitation and evapotranspiration that lead to decreased reservoir inflows (Bahl, Linn, and Wetzel 2013; Lima, Lombardo, and Magaña 2018; Melo et al. 2016; Semensatto et al. 2021; Taffarello et al. 2017; 2016). Degradation of source watersheds is currently costing $22 million dollars annually in sediment pollution control in the Cantareira system alone (Ozment et al. 2018).
- Informal settlements degrading water quality: The proliferation of informal urban settlements, locally known as favelas, in river basins both within and adjacent to the RMSP have led to several water quality problems making local water sources unfit for water supply. This is particularly true in the last decade, when water quality indicators in four reservoirs in the metropolitan area have degraded as a result of eutrophication, particularly from increasing untreated wastewater (Semensatto et al. 2021).

Numerous SWP and diversification measures have been implemented to improve RMSP's urban water resilience, most of which targeted establishing the enabling environment for IWRM, watershed restoration interventions, and innovative financing mechanisms.

Institutionalizing WRM

At the federal level, the National Water Resource Policy (Law No. 9.433, 1997) was passed in 1997 that aimed to decentralize the decision-making processes to manage water at the basin level by creating River Basin Committees that would ensure the participation of a diversity of stakeholders. The RMSP is covered by the Alto Tietê River Basin Committee (CBH-AT), which includes the city's area, and the Piracicaba-Capivari-Jundiaí (PCJ) Rivers Basin Committee, which includes the area where the city sources its water supply. Both River Basin Committees were established prior to the law. According to this structure, regulatory, permit, and infrastructure decisions should only occur at the state and federal levels under special conditions, for example in cases where water courses cross state lines or projects cover multiple river basins (de Moraes 2015). River Basin Committees are made up of sub-committees, the membership of which is very often limited to technical experts appointed by managers and the state (Rothberg et al. 2018). To deal with this difficulty, committee members have proposed further decentralization of the committees (particularly in complex urban catchments such as the Alto Tietê River Basin), appointing a greater diversity of civil society positions, and making committee and technical committee meetings easier to attend geographically.

Anticipating Future Transboundary Water Conflicts

Interbasin transfers currently make up 14% of the RMSP's water supply and have the potential to increase if certain long-term source development projects gain enough political support (TNC 2023b). To address potential conflicts over Brazil's disproportionate distribution of water resources, the ANA was created to implement national water policy, and grant and manage water use permits for federally managed rivers (de Souza Leão and De Stefano 2019). Through ANA, the federal government has jurisdiction over waters that cross state or international boundaries, while water supplies located entirely within a single state, including groundwater resources, are in the state's domain, except for when they are used by federal infrastructure projects (Johnsson and Kemper 2005). Federal oversight includes the formation and management of the National Council of Water Resources, which is charged with coordinating federal, state, and regional planning and arbitrates conflicts (MDR, 2022).

Streamlining Planning

In response to the increasing complexity in the water resources system, the State of São Paulo passed its first State Water Plan in 1990 and the São Paulo State Water Law shortly after (Law 7663, 1991), which would spearhead the aforementioned Law No. 9.433, 1997 (de Souza Leão and De Stefano 2019). The 1991 law created the Integrated Water Resources Management System of São Paulo (SIGRH), which consolidated planning and decision-making regarding water resources into a single structure that brought together previously uncoordinated governing bodies (Silva 2017). SIGRH is formed by the State Council of Water Resources, the Coordinating Committee of the State Plan for Water Resources that mainly advances tools and technical capabilities to support the development of the regularly produced State Water Plan, and the twenty-one River Basin Committees of the State of São Paulo. Following the implementation of State Decree 56.635, 2011, the Secretariat of Sanitation and Water Resources (SSRH) became the main arm of State power over the SIGRH, responsible for carrying out studies, planning, construction, and operation of water resources infrastructure works, as well as preparing support plans and programs for municipalities and related basins (Silva, 2017). Similarly, the budget of the State Water Resources Fund (FEHIDRO), and the structure of the Guidance Council of the State Water Resources Fund (COFEHIDRO) that administers the fund as low interest loans or grants for projects and activities approved by the River Basin Committees are governed by the SSRH (Silva 2017).

Financing Watershed Management and Restoration

In an effort to begin stable funding for water resource and related environmental projects, the State of São Paulo instituted its first water tariffs to urban and industrial users after Law 12.183 was passed in 2005, starting with the PCJ basin in 2007 and with only one of the 22 basins left without tariffs as of 2022 (Coordenadoria de Recursos Hídricos 2022). According to the state, the tariff is meant to promote the rational use of water and fund the programs and actions outlined in the water supply and sanitation plans. The tariffs have raised between R$10.6 million in 2007 and R$171.8 million in 2021 for the FEHIDRO (COFEHIDRO 2021; TV Água 2018). Importantly, the tariff is applied to the water quantity of the permit rather than the use to encourage more conservative requests for bulk water by users (Johnsson and Kemper 2005).

In 2005, TNC and the municipality of Extrema launched the *Extrema Conservador das Águas* (Extrema Water Producers) Program, a PES scheme financed through the Municipal Public and Private Fund for PES (*Fundo Municipal para Pagamentos por Serviços Ambientais*), which receives state tax revenue, water use fees from the PCJ basin and national and international institutions (Mamedes et al. 2023; Richards et al. 2015). By 2016 it had reforested 216 ha, conserved 6,378 ha, engaged 224 farmers, and secured the commitment of the municipality to allocate approximately 3% of its municipal budget to supporting future natural infrastructure efforts (Ozment et al. 2018).

Led by the São Paulo government, the *Programa Nascentes* coordinates the restoration of priority degraded areas by connecting private companies who must meet habitat mitigation obligations with public agencies and resources to select projects to fund based on a weighted scoring system (Ozment et al., 2018). It does so by hosting an online portal that matches companies looking for offsets for environmental degradation with landowners willing to restore. Over the past six years, the program has resulted in the restoration of 21,000 ha (Ozment et al. 2021).

The São Paulo Water Fund was created in 2007 through the efforts of TNC and a broad coalition of stakeholders to promote conservation and green infrastructure in the Cantareira and Alto Tietê watersheds and funds projects associated with *Programa Nascentes*, the PCJ River Basin Committees, the Extrema Water Producer Program, and the PCJ Water Producer Program (Ozment et al. 2018). As of 2018, it has a total investment of $32 million dollars (TNC 2021).

Supplying Water to Informal Settlements

Sabesp works with community organizers and municipalities to regularize illegal settlements and install water meters to households that agree to register and pay a water bill, giving them de facto tenure security (Hylton and Charles 2018). With a goal of regularizing 160,000 connections of the more than 400,000 estimated clandestine connections in the RMSP, the *Água Legal Program* provides recipients with improved water, fewer service interruptions, and social benefits, including jobs for community residents to register and install connections, and a proof of address for marginalized individuals giving them the ability to enroll children in daycare and apply for other public services (SEC 2018). This innovative program aims to eliminate 3.3 billion liters of physical and commercial losses per month through upgrading physical infrastructure, installing water meters, administratively recognizing connections, and engaging in social outreach to reduce consumption in informal areas (Hylton and Charles 2018).

APPENDIX C: SUMMARY OF SOURCE WATER PROTECTION AND DIVERSIFICATION MEASURES

Table C1 summarizes key SWP measures at the watershed and aquifer level that have been successful in providing additional security for urban water systems (either individually or in combination), in terms of both quantity and quality, while also protecting ecosystems, including nature-based solutions, regulation, and other measures. Further information about watershed interventions and their benefits is available in USAID's Water Resources Management Technical Brief.

The relevance, likely impact, and factors for success of these measures depend on the biophysical setting, ecological, hydrologic, and climatic conditions of a given source of water, as well as sound planning, governance and finance (Hamel and Tan 2022; UN WWAP/UN-Water 2018).

Table C1. Successful source water protection measures

Category	SWP Measure	Description
Nature-based solutions (NBS)	Wetland conservation	NBS are inspired and supported by nature and use, or mimic, natural processes to contribute to the improved management of water. NBS can involve conserving or rehabilitating natural ecosystems and/or enhancing or creating natural processes in modified or artificial ecosystems.
	Forest conservation	
	Revegetation	
	Green agricultural practices[27]	
	Green stormwater management[28]	
Regulation	Land use policies, plans and implementation	Use of laws and regulations at various levels of government to protect source water within a watershed.
	Wastewater permitting	
	Zoning for protected areas	
Other measures	Purchase of land for conservation	Other measures that have been successful in protecting source water for urban and other uses, as well as for preserving ecosystems.
	Wellhead protection	
	Public education	
	Wastewater treatment	

(Echavarria, Cassin, and Bento da Rocha 2021; Gammie and De Bievre 2015; UN WWAP/UN-Water 2018; United Nations Environment Programme, UNEP-DHI Centre on Water and Environment, and IUCN 2018)

Diversification measures can include both strategies to increase the supply of water or to address water demands. Successful diversification measures are listed and described in Table C2.

Table C2. Successful source water diversification measures

Category	Diversification Measure	Description

[27] Includes activities such as conservation tillage, agroforestry, nutrient management, or grazing management

[28] Includes activities such as rainwater capture, sand dams, or half moons

Supply-side Options	Use of surface and groundwater resources	Expansion of use of surface and groundwater resources to supplement existing sources and increase overall water supply.
	Unconventional water sources (including desalination, stormwater reuse, wastewater reuse, gray water)	Desalination is a process to remove salt from seawater or brackish groundwater to allow for its use in urban water supply systems (as well as other uses). Gray water systems are designed to separate non-toilet household wastewater for non-potable uses such as toilet flushing or irrigation. Wastewater reuse is conversion of municipal or industrial wastewater into water that can be reused for a variety of purposes (sometimes referred to as water recycling). Stormwater reuse implies structural controls to remove pollutants from stormwater runoff for use to supplement urban water supply.
	System redundancy and inter-connections	Inter-connecting independent water systems can be an effective approach for providing emergency water supplies when one area is affected differently from another and for integrating water supplies from various sources.
	Water storage	Water storage, from large scale (reservoirs) to small scale (household storage tanks), can assure water delivery during peak demand periods and dry seasons.
	Groundwater management and aquifer recharge	Groundwater management can include policies and management plans to prevent over-abstraction of groundwater, and managed aquifer recharge can increase water supplies.
	Water trading and water banking	Water trading is a process of buying and selling water rights, either permanently or temporarily, while water banking is a way to postpone exercise of water rights (water deliveries) during some periods so that they can be used later.
Demand-side Options	Addressing physical water losses	When system leakage is reduced, more water is available for all demands of urban water systems, increasing the reliability of the system and decreasing the need to secure new water resources.
	Demand management	Demand management encompasses a set of options that water suppliers and policymakers can use to reduce water consumption, including installation of water-saving devices, public education, water restrictions, and pricing.

(Bichai, Kajenthira Grindle, and Murthy 2018; Leonard, Walton, and Farbotko 2015; Luker and Harris 2019; Luthy, Sharvelle, and Dillon 2019; Srinivasan, Gorelick, and Goulder 2010; United Nations in Jordan 2022; Worku 2017)

Diversification as an explicit strategy in water supply planning is relatively new. Very few articles explicitly use the terms "diversification" or "diversified portfolio" for water planning, especially in LMIC settings. However, each of the case study cities had implemented several measures to diversify their water sources.

APPENDIX D: TYPICAL DATA REQUIREMENTS FOR WATER RESOURCES PLANNING MODELS

INTRODUCTION

Water resources models vary in what aspects are included. Some models focus just on hydrology, such as SWAT, some on water quality, such as QUAL2K. But within each category of modeling there are typical data requirements or ideal sets of data in order to be able to develop, calibrate and validate the models. Even within a particular category of a model, the scenarios of interest to stakeholders can vary, which may require additional data. For example, the stakeholders may want to focus on the impact of droughts, which would require the inclusion of climate projections, possibly data on crop yield response to water scarcity, etc. The data requirements listed below are a sample of what may be needed, depending on the specific geography and the interests of the stakeholders examining a particular aspect of water resources. Questions they might ask could include:

1. How do changes in surface water inflows to dams brought about by climate change affect the reliability of water deliveries?
2. How does continued sediment loading into reservoirs impact available storage and reliability of water deliveries?
3. What will happen to groundwater storage/levels under a new hydrological regime brought on by climate change if pumping continues at current levels? By extension, what is the safe yield of aquifers under different assumptions of recharge?
4. How will current development trends impact water quality and what are the implications for water treatment?

Subsequently, the model could consider policies and/or interventions aimed at addressing these vulnerabilities by asking questions such as:

1. How can existing dams be operated to maximize safe yield of surface and groundwater supplies?
2. How would new infrastructure serve to improve system performance?
3. To what extent can supply augmentation (e.g. rainwater harvesting) be used to enhance water security?
4. To what extent can demand management (e.g. loss reduction, crop shifting) be used to enhance water security?
5. What level of water treatment will be required to ensure adequate water quality for water users?

The following discussion describes some of the standard data that are needed to create components of a WR model.

RIVER NETWORK

While not always required, river networks are ideally mapped to match the physical reality.

Data requirements:

- GIS shapefile of rivers.

WATER DISTRIBUTION NETWORK

The distribution of water can be done in a variety of water conveyance facilities – e.g. canals, tunnels, pipelines.

Data requirements:

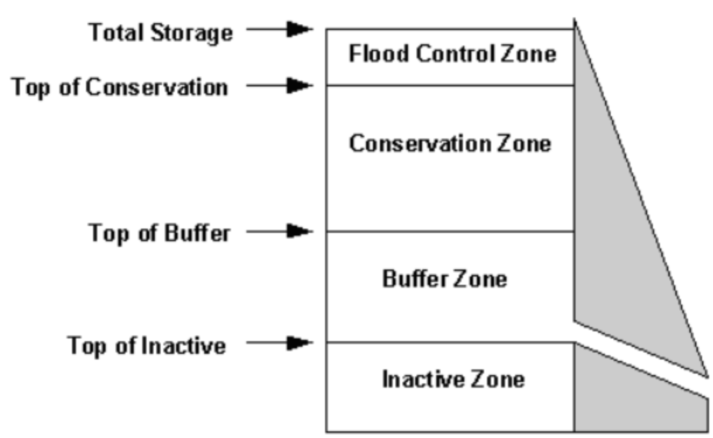
- Maximum flow capacity
- Losses. These data are important when considering reducing non-recoverable losses, which is a focus of many water systems.
- GIS shapefile of canals and/or pipelines.

SURFACE WATER STORAGE

The storage of water is a critical component to include in any WR model. Storage can be in the form of reservoirs, small ponds, rainwater harvesting, etc.

Data requirements:

- Storage Capacity
- Net Evaporation. This may be input directly or calculated from Precipitation and Evaporation inputs.
- Volume-Elevation Curve. This is needed to calculate changes in storage as net evaporation adds or removes water from storage
- Time-series of observed storage/levels. These data are used for calibration purposes.
- Storage/Release Operations
  - Top of Conservation. Typically used to define operational rules for flood storage
  - Top of Buffer. This is used to limit releases once storage levels drop below a certain threshold.
  - Top of Inactive. Also known as “Dead Storage.” This is the bottom of the active storage zone



- Hydropower Operations
  - Max Turbine Flow
  - Tailwater Elevation
  - Plant Factor

- Generating Efficiency
- Energy Demand
- Hydropower Priority

RAINFALL-RUNOFF/HYDROLOGY

DISAGGREGATION

When considering rainfall-runoff processes, it is standard practice to disaggregate the basin into several sub-basins. The number of sub-basins depends upon the purpose for which the model is being used and the scale at which the user wants to view model outputs.

In addition to disaggregating the basin into multiple sub-basins it may be useful to disaggregate sub-basins based on the distribution of geophysical properties (e.g., elevation, land cover, soil type). For example, this may be useful for evaluating scenarios that consider changes in snowpack at different elevations or the conversion of land from one type of land cover to another. he choice for how to disaggregate sub-basins depends upon the focus of the study being conducted and the questions that need to be addressed. In general, GIS layers are used to inform this disaggregation process. Some of the data include:

- Digital elevation model. This is used for disaggregating sub-basins based on elevation, slope, and/or aspect.
- GIS shapefile of land cover/land use. Disaggregating based on land cover is necessary when considering land conversion scenarios.
- GIS shapefile of soil type. Disaggregating based on soil type may be done when evaluating soil erosion.

METHOD

There are different ways of simulating rainfall-runoff that can range from simple coefficient methods to more complex. While the simpler methods require less input data and are generally easier to implement, they do not account for antecedent soil water conditions, which can significantly influence hydrological response. Data requirements for all methods include:

- Area. This is needed for each sub-branch added to the catchment.
- Precipitation. Historical time-series climate data obtained from local stations should all cover same time period in order to calibrate the model. For calibration purposes, historical climate data should cover several years (typically a minimum of 10 to 30) and include a range of wet and dry periods.

Additional data required for each type of method are summarized in Table D1.

Table D1. Additional data that may be required for each method

Simplified Coefficient Method	More Complex Methods
• Reference Evapotranspiration	• Temperature • Relative Humidity • Wind • Latitude * *Note, each ideally would have* a 20-30 year record

CALIBRATION

Regardless of which method is chosen to simulate rainfall-runoff, the model should be calibrated to ensure that simulated runoff adequately captures the real-world hydrology. These calibration data include:

- Time-series of streamflows at various locations throughout the basin
- Time-series of evapotranspiration.
- Time-series of snowpack/accumulation

WATER DEMANDS

Demands for water are a critical component to any WR model. Typically demands are disaggregated around household demands, industries, and agriculture. There are a range of disaggregations possible within these categories of demands. They can be given as single estimates, but ideally, there is a further disaggregation that allows an exploration of how demands can change in scenarios.

Typical data required includes:

- Households, commercial, industrial, public, etc.
  - Number of people/employees.
  - Per capita water use rate or per unit of industrial output.
  - Water use variation throughout the year.
  - Percent of water returned to system. Water that is not "consumed" may return directly to surface water or groundwater or to wastewater treatment plant.

IRRIGATED AGRICULTURE

Irrigated agriculture typically represents a significant water user in many basins around the world.

DISAGGREGATION

The logic for disaggregating irrigated areas within a basin follows the same process as that for disaggregating a basin into several sub-basins. First, one must decide the appropriate scale for determining the base unit for irrigated areas. This is most often determined by location within the basin, water sources, and/or contractual factors. Some of the data types used in the process include:

- GIS shapefile of irrigated areas or other data source that can identify the location of irrigated areas within the basin.
- Water source(s) for each irrigated area. It is important to understand where each irrigated area is receiving water from – i.e., river abstraction, groundwater pumping, canal.
- Contractual information. This information helps to understand allocation priorities.

Once irrigated areas are identified within the basin, each catchment may be subdivided based on the area of different crop types within the irrigated area. The number of different crops generally ranges from a couple of types to a couple dozen types. The degree of disaggregation depends upon data availability. These data may include:

- Crop surveys. These are tabular data that report annual cropped areas for different crops. Ideally, these data should be available for several years in order to identify trends and to properly calibrate their water usage.
- Crop water use patterns. These data are needed to calibrate the model.
- Crop yield/production.

METHOD

There are at least four different ways to simulating crop water demands: (1) the simplified coefficient method, (2) the soil moisture method, (3) MABIA, and (4) the plant growth model. These range in their degree of complexity from very simple to complex, which is also reflected in their data requirements. Each approach shares some basic data requirements, including:

- Irrigated area.
- Planting and harvesting dates.
- Crop coefficient, Kc. This typically varies between planting and harvesting dates.
- Precipitation.
- Yield/production:
  - Potential yield, and
  - Yield response factor.

Each method may require additional data, which are summarized in Table D2.

Table D2. Additional data that may be required for each method

Simplified Coefficient Method	Soil Moisture Method	MABIA	Plant Growth Model
• Reference evapotranspiration • Irrigation efficiency (recommended, but not required)	• Temperature • Relative Humidity • Wind • Latitude	• Daily precipitation • Minimum and Maximum daily temperature • Relative Humidity • Wind • Latitude • Irrigation efficiency • Fraction of soil wetted by irrigation • Irrigation schedule	• Daily precipitation • Minimum and maximum daily temperature • Relative Humidity • Wind • Latitude • Irrigation schedule • Irrigation rate • Irrigation distribution uniformity • Soil layers

CALIBRATION

The data required to calculate water use by irrigated agriculture:

- Annual crop water use rate,
- Surface water and groundwater deliveries to each irrigated area (recommended, but not required), and
- Crop yields/production.

WASTEWATER TREATMENT

Wastewater treatment and the potential for wastewater reuse should be included as relevant.

Data Requirements:

- Daily capacity.
- Consumption. Amount of water entering the facility that does not return to the system as treated water.
- Capacity for wastewater reuse and associated infrastructure.

FLOW REQUIREMENT

Flow requirements can be for keeping water in rivers to support ecosystems and aquatic habitats or for keeping flows above certain levels to support other purposes – e.g. navigation, health and safety concerns, supporting the livelihoods of riparian communities, etc. The flow requirement may be as simple as a constant value; it could use a recurring pattern of flows; or it could be calculated using an expression based on antecedent conditions. Each case will determine the complexity and the manner in which the flow requirement is expressed.

STREAMFLOW GAUGE

Observed streamflow data are used calibrate the model. In general, it is recommended to calibrate to several streamflow gauges throughout the basin. The calibration process generally begins by focusing on gauges that are at points upstream in the basin that are relatively unimpaired by water use and continues to gauge further downstream that may reflect a higher degree of impairment.

Data Requirements:

- Time-series of observed streamflow

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