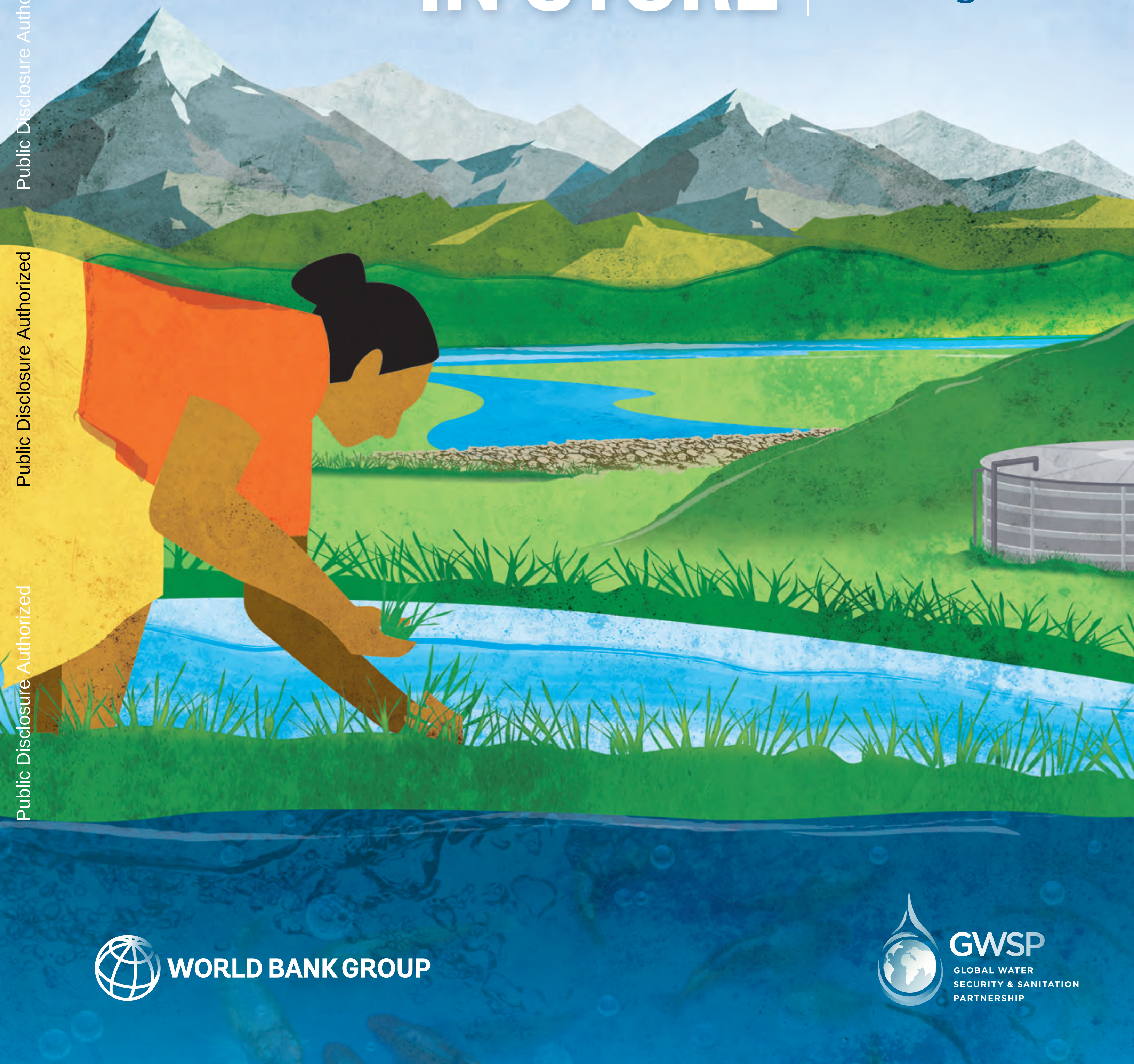
WATER GLOBAL PRACTICE

WHAT THE FUTURE HAS IN STORE

A New Paradigm for Water Storage



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FOREWORD

As climate change impacts escalate, the importance of freshwater storage is rapidly scaling the global agenda. Rising temperatures are scorching already-parched landscapes in some parts of the world, while floods inundate others. Countries from Australia to Zimbabwe are struggling with both water extremes, along with the concurrent threat of forest fires. In the last year alone, Europe, one of the world's most temperate regions, has seen record temperatures, widespread water shortages, and massive flooding. Worldwide, the toll in human suffering, economic loss and instability, and environmental destruction is devastating. In some regions, the weather is erasing decades of gains in human development in a matter of days.

It is often said that climate change expresses itself through water. The inevitability of hydrological climate extremes is placing increasing pressure on all water practitioners to manage differently, and nowhere is that more necessary than in storage. Freshwater storage is at the heart of adapting to climate change, most obviously by saving water for drier times and reducing the impact of floods. Many populations are experiencing increasing levels of climate-based turmoil, and for them, any relief that comes with recovery is tempered by anxiety about the future. It is safe to say that going forward, the most stable, durable societies will, in many cases, be anchored in more resilient approaches to water storage.

However, as this report illustrates, the world is facing a growing freshwater storage gap. Just as we need more storage, the actual volume of freshwater storage is in decline, primarily due to the loss of natural storage, but buttressed by an underinvestment in the maintenance of built storage that increases vulnerability overall.

Improving how water storage is planned and managed is about more than climate. Securing reliable water services is also a fundamental part of socioeconomic development, underpinning progress towards not just SDG 6—"clean water and sanitation for all"—but also for the multitude of other SDGs that rely on water. The most recent SDG progress reporting (2021) suggests that approximately one-quarter of the world's population lacks access to safely managed drinking water services, and 108 countries are unlikely to have sustainably managed water resources by 2030. Additionally, water storage services are clearly linked to goals in poverty, food security, energy, economic growth, sustainable cities, the environment, and climate.

The World Bank has produced this report because we recognize that many of our clients around the world are in unprecedented situations, struggling to cope with water-related disasters and grappling with how to develop, operate, and maintain more—and more resilient—water services. Climate change, twinned with a growing water storage gap, means traditional approaches to water storage must evolve. In developing our understanding of what a twenty-first century approach to freshwater storage could look like, the Bank reflected on its own many decades of experience with natural and built water infrastructure, searched the world for examples of water storage solutions that are not otherwise accessible to water practitioners focused on their local regions in isolation, and looked at the variety of new science and tools that could be brought to bear to achieve results.

There is no simple path forward; the solutions we need to invest in to meet our common challenge are many and complex. We must harness the power of nature and supplement it, where necessary, with built storage. We must take better care of our existing storage, and use it to meet the needs of multiple sectors, populations, and the environment. Critically, we need to do this while recognizing that all storage, big and small, natural and built, underground or on the surface, is part of a bigger water cycle and system that too require understanding and investment.

The need for a new water storage paradigm is clear. As this report illustrates, ultimately, true resilience lies at the system level rather than in individual storage facilities—and that requires a change in thinking and approach on the part of water resource innovators across the spectrum. *What the Future Has in Store: A New Paradigm for Water Storage* proposes the purposeful design of water storage solutions that impact many instead of few. Applying the concepts presented could manifest the kinds of resilient, sustainable, even life-saving storage services that both mitigate the impact of climate-related disasters and secure a water future for generations.

The ideas, examples, and tools contained here will help a variety of stakeholders begin to put a new approach into action. However, genuinely integrated approaches to storage at scale are still being developed, so the science of the possible is not yet fully known. For the World Bank, this report represents one step in a journey toward a new storage paradigm. It is a journey that will continue for years to come as the intertwined challenges of climate change and development continue to reshape the world around us.

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EXECUTIVE SUMMARY

1. INTRODUCTION: A NEW PARADIGM FOR WATER STORAGE

The most urgent challenge of our lifetime is water.

Worldwide, water crises are taking an astounding toll on people, environments, and economies. At the writing of this report, nearly two-thirds of all municipalities in Mexico are facing a water shortage, leaving desperate people queueing for rations; France is in the grip of the worst drought in its history, forcing 93 regions into restricted water use and trucking water into another 100 municipalities where the pipes have completely run dry; at the other end of the spectrum, four separate flooding events in 11 days—each qualifying as a 1-in-1,000-year rainstorm—have left parts of the United States reeling, washing out roads, swamping city streets, and drowning entire towns. Meanwhile, in Pakistan, flooding has submerged around one-third of the country, killing over 1,200 people and displacing a further 33 million.

Water and water-related disasters are rated among the greatest risks facing modern societies (WEF 2022). When water isn't available at the right time in the right amount, communities large and small can teeter on disaster.

For millennia, water storage has helped humans cope with the natural extremes of water availability, meeting freshwater demands by increasing and regulating the volume of accessible water. Today, household wells, reservoirs, dams, tanks, and other built systems work symbiotically with mountain glaciers, coastal floodplains, wetlands, and aquifers to form a web of natural and built freshwater storage solutions that people depend on for drinking, sustenance, transportation, recreation, for regulating flows for hydropower, and mitigating the destruction of floods.

But we are at a crossroads. The global population has doubled over the last 50 years, and parallel economic growth has translated into a rapidly increasing demand for water—yet the total volume of freshwater storage has declined by around 27,000 billion m^3 (McCartney et al. 2022), due to melting glaciers and snowpack and the destruction of wetlands and floodplains. Concurrently, the volume of water stored in built storage is under threat as sediment fills the useful storage space in reservoirs (Annandale, Morris, and Karki 2016), new construction in some large infrastructure solutions have proven far less sustainable than anticipated, and built structures are aging faster than the pace of rehabilitation.

In short, we are facing **a global water storage gap** (GWP and IWMI 2021).

Exacerbating the problem is climate change. Nowhere is the impact of climate change more visible than in water. Over the past 20 years, 1.43 billion people have been adversely affected by drought (Browder et al. 2020), leaving human settlements and industries of all sizes without sufficient storage to meet growing water demand from people, farms, and industry. Conversely, 1.65 billion were adversely affected by floods, with an estimated 290 million people directly affected—an increase of 24 percent over previous decades (Browder et al. 2021; Tellman et al. 2021; CRED and UNDRR 2020). By 2030, projections suggest an additional 180 million people will be directly affected by flooding (Tellman et al. 2021), the poor and disadvantaged primarily among them.

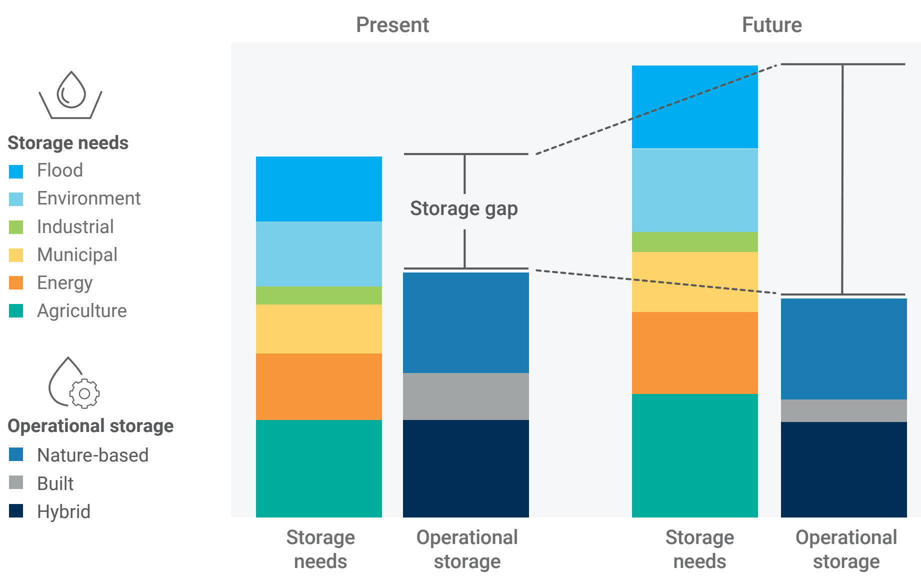
What makes this issue progressively more urgent is that the water storage gap—the difference between the amount of water storage needed and the amount of operational storage (natural and built) that exists for a given time and place—**is growing and is expected to widen** (figure ES.1, McCartney et al. 2022; GWP and IWMI 2021).

Closing the water storage gap is our shared challenge. It is an inherently complex mission made exponentially more difficult by the fact that **current approaches to freshwater storage development and management are inadequate to meet the challenges of the twenty-first century.**

From decision-makers at water ministries and ministries that are water-reliant, to engineers, ecologists, and academics, to project teams at the World Bank and other international development agencies, we recognize water storage as a dense web of interdependent natural, built, and hybrid solutions—**but rarely is it planned and managed as a system.** Most often, water managers approach solutions as separate units, evaluating, designing, developing, and managing storage as independent facilities for a limited set of stakeholders, developing fragmented solutions that are overly reliant on built infrastructure, insufficiently focused on the ultimate service, inadequately maintained and operated, and benefiting a finite group without considering the potential to develop service solutions with a broader reach.

Intercepting the scale of change to the climate that is underway and achieving a meaningful shift in approaching water storage mean confronting long-standing traditions in planning and development cooperation and coordination. "Business as usual" isn't an option.

FIGURE ES.1 The Growing Storage Gap



Source: Adapted from GWP and IWMI 2021.
Note: Amounts of storage needed and operational storage are stylized estimates.

***What the Future Has in Store: A New Paradigm for Water Storage* calls on us to think differently, plan inclusively, and act systematically to address the water storage challenges of the coming age**. Grounded in the principles of integrated water resources management (IWRM), it provides a framework for accelerating collaboration between sectors and public and private stakeholders globally, setting out a strategy for tackling and overcoming the storage gap, and tables an imperative for the whole spectrum of vested water stakeholders to begin championing integrated storage solutions managed as a system to provide long-term, resilient, and sustainable services that benefit many for generations to come.

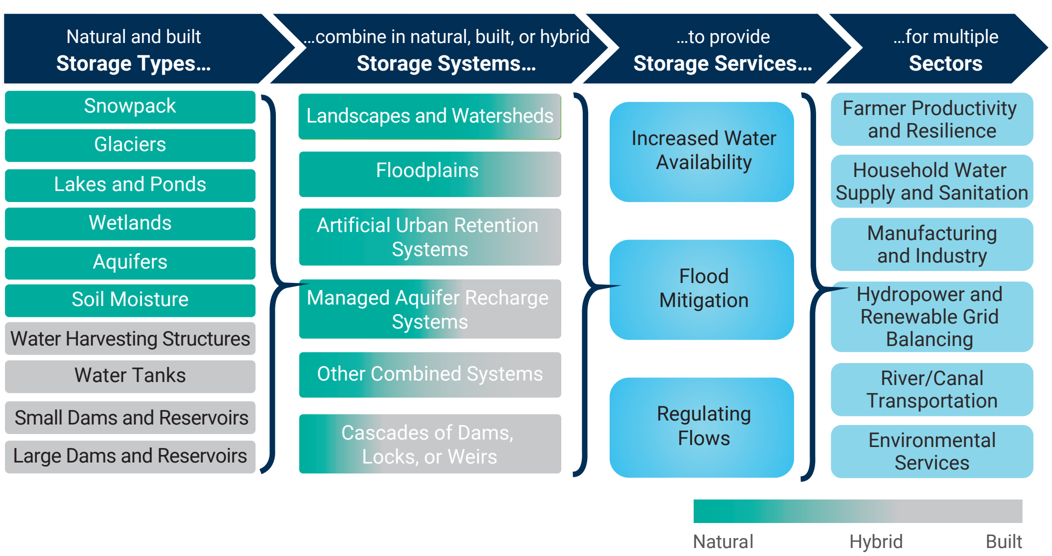
2. THE CHALLENGE

Water is at the center of economic and social development. It influences whether communities are healthy places to live, whether farmers can grow food, or whether cities have reliable clean energy. Water underpins natural ecosystems, drives industry, and creates jobs. It touches every aspect of development, with a direct link to almost every Sustainable Development Goal (SDG).

Over 99 percent of freshwater storage is in nature (McCartney et al. 2022), making it a large part of the solution, but multiple forms of water storage—built and natural—usually combine into storage systems where elements work together to provide the services communities rely on (figure ES.2). For example, floodplains and wetlands combine with river channels and soil storage, buffering flood water and releasing water in drier periods. Several smaller storage systems may combine into larger systems. The flood vulnerability of a city, for example, will be influenced by surrounding systems of land use, groundwater recharge, and floodplains, as well as local flood mitigation measures.

The distribution of water across continents, countries, and basins varies significantly in quantity, quality, and seasonality. Within countries themselves, water is distributed unevenly. Rainfall, surface, and groundwater can all vary considerably within countries; for example, in the United States, the wettest areas can receive roughly 100 times the rainfall that the driest areas receive. Huge variations in rainfall

FIGURE ES.2 Water Storage Types, Systems, and Services



Source: Original figure for this publication.

exist in many other countries, as varied as India, Colombia, Peru, and Papua New Guinea (Damania, Desbureaux, and Zaveri 2019). Ground and surface water is also geographically dispersed, leaving many countries relying on either natural conveyance systems—including rivers—or built infrastructure to move water from wetter to drier areas.

Broadly, water storage provides three main services: (a) improving the availability of water during drier periods, (b) mitigating the impacts of floods, and (c) regulating flows for other purposes, such as hydropower, transportation, or recreation. **These services, in turn, underpin everyday water use across most economic sectors, from agriculture to transportation (figure ES.2).**

Water storage is becoming more important as a vital tool for adapting to, and mitigating, climate change. Climate change can increase variability and water extremes, change the total water available, and increase water needs. Because climate change is bringing less predictable and more variable precipitation, it depresses economic investment and job creation, and it makes farmers less productive and the provision of everyday services, such as reliable urban water supply, more difficult.

Water storage provides a mechanism to offset some of the hydrological changes brought about by climate change by improving water availability and reducing the impact of floods. Further, water storage is expected to play an important role in mitigating drivers of climate change; for example, hydropower provides a source of clean energy and is used to incorporate other variable renewable energy sources, such as solar and wind, into the grid, as well as to store energy, using technology such as pumped storage. Careful management is needed to balance these new demands on the storage resource, as well as to minimize greenhouse gas (GHG) production from reservoirs, paddy fields, and other storage types.

The Complexity of Storage Planning

Addressing the storage gap is inherently challenging, in part because each situation is scale- and context-specific. Measures to fill the storage gap must be fit for purpose, depending on the local conditions, as some countries may experience less pressure while others already have significant water storage gaps, which may worsen over time. Some locations may require changes to the operation of existing water storage infrastructure or institutional setup to optimize their existing storage operation. In Lake Mendocino, California, the United States Army Corps of Engineers (USACE) and other stakeholders are piloting new reservoir operating rules that will allow for improved flood management (case study B, chapter 8). Other systems may require a comprehensive intervention to expand the volume of water storage available to provide services. In addition to new built storage, Monterrey, Mexico, has been working to expand natural storage upstream of the city through participatory catchment management programs to provide flood protection services for the city and its assets (case study D, chapter 8).

Ultimately, all water storage gaps are local, measured in simplest terms by supply versus demand. In any system, storage demands occur at varying scales, times, and volumes, with requirements related to reliability, vulnerability, resilience, and control. On the supply side, availability depends on natural, built, and hybrid storage, with combinations offering a variety of advantages in terms of scale, timing, volume, and service.

For any given location, **the practical responses to addressing storage gaps include considering other water resources management measures, including non-storage measures**, as part of a broader approach to water resources. Despite the local nature of water storage gaps, for many, addressing the challenge will require working across borders, given that many river basins and groundwater aquifers are transboundary.

One of the primary challenges we face is that failure to plan storage as a system often results in overreliance on built storage and overlooking the value of natural storage. Built storage is generally understood to be providing direct services to people, and the fact that natural storage has always been there makes it somewhat invisible and taken for granted. Different types of storage are often developed (frequently, built storage) or degraded (both built and natural storage) in response to various needs or pressures, without full consideration of how natural and built storage can be managed and operated as a system.

Siloed approaches to scaling up storage traditionally suffer from other primary challenges, including:

- » The drive for new storage often eclipses opportunities for making better use of existing systems through rehabilitation, reoperation, and retrofitting actions.
- » Short-term financial and political incentives often motivate the development of new storage without full consideration of options that would increase services provided by existing natural and built storage.
- » Multiple competing storage systems serve different stakeholders with different services, often separated by borders or boundaries, leading to uncoordinated development or water releases and reduction in benefits overall.
- » Properly understanding costs, benefits, risks, and uncertainties in advance of investment decisions can be time-consuming, expensive, and difficult. They are not always well understood. As a result, negative impacts on people and the environment are not always minimized and mitigated, and solutions are not developed with an eye toward distributional equity.
- » Insufficient maintenance of existing storage is driven by several factors including inadequate attention to preserving natural storage, sedimentation of built storage, and poor operation and maintenance (O&M).
- » Storage is unable to meet growing risks of climate change or protect the value of investments. Climate change may mean that storage systems need to meet new performance requirements to provide the same services or need to be altered for safety concerns, such as to handle increased floods.
- » Policy and institutional measures are often lacking. Without these, water storage runs the risk of limited sustainability, and in some cases, may be counterproductive. Large new storage for urban water supply, for example, might facilitate an increase in water consumption beyond what had been anticipated as new supplies become available.
- » Overreliance on storage when there may be other more efficient solutions, such as demand management or valuation or pricing of water; supply-side alternatives, such as desalination or treated wastewater; or non-water alternatives to energy and transportation.

There is no simple solution to these complex challenges, but focusing on the underlying reasons for them provides a path to better approaches. To measure and model in an integrated way to close the water storage gap is the ultimate objective that begins with the need to think differently about storage planning.

3. A FRAMEWORK FOR INTEGRATED WATER STORAGE PLANNING

What the Future Has in Store: A New Paradigm for Water Storage sets out a new framework for integrated water storage planning. It presents an approach to systemically address the issues surrounding storage to improve water security and water availability at every level as actioners seek answers to three questions:

- ***What interventions do I need to put in place to meet my water security goals?***
- ***How is that accomplished while minimizing negative impacts?***
- ***What forms of water storage development and management are part of the solution?***

The proposed integrated approach to water storage planning fits within broader IWRM, with the river basin as the primary frame of reference. The framework builds on the IWRM planning approach, with a focus on concurrent joint planning around solving specific water-related problems through storage or other management measures. It describes potential approaches to filling the storage gap, starting with the need to consider the full range of choices—including demand management, alternative supply mechanisms, and storage—that may be required at the local level. Whether considering natural or built, surface or sub-surface, small or large, one of the framework's main purposes is to provide a systematic process for early identification and consideration of potential opportunities and trade-offs that often receive attention after significant sums have been invested in project preparation and some design choices have already been made.

A Problem-Driven and Systems Approach

Where storage planning often occurs at a project level, the integrated framework moves beyond the status quo, combining **a problem-driven approach and a systems approach.** Together, they provide a more strategic and robust alternative to conventional planning by considering interconnected water resources management components across storage types, scales, and user needs.

A **problem-driven approach** entails defining the problem and identifying the underlying challenges that require solving. The concept is used across numerous fields where the solution designers (software developers, engineers, biological or pharmaceutical design teams, and social scientists, among others [Fritz, Levy, and Ort 2014]) delve into and define the underlying problem first, rather than beginning from a set of design specifications. Water-related challenges may include impacts of natural disasters, inadequate water supply for household consumption, agricultural or industrial production, reduced electricity generation, potential threats to biodiversity, environmental flows and ecosystem services, reduced transportation for goods and people, and limited recreational opportunities. Targeted development objectives are formulated from the problems identified.

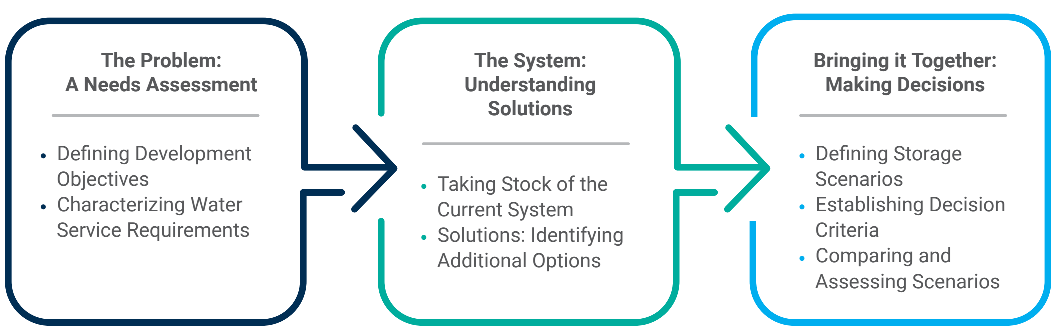
A **systems-driven approach** allows for an integrated look at the solutions, stakeholders, impacts, and alternatives. It considers necessary enabling systems and services, the roles played by different parts of the system, and the relationships among those parts with respect to the overall behavior and performance of the system, leveraging interconnections to build integrated approaches to development problems that weave together geographic, socioeconomic, and institutional factors. For example, a connected water storage system can support integrated flood and drought management by transferring flood excesses to periods of scarcity through measures such as managed aquifer recharge (MAR) fed by diverted floodwaters, as is being done with the "Underground Taming of Floods for Irrigation" approach in the Ganga Basin. Integrated flood and drought management is also supported by forecast-informed reservoir operations as in Lake Mendocino, California.

Bringing the problem-driven and systems approaches together into a single framework leads to potential solutions not considered by one approach alone. **As an options assessment, the framework is intended as an early planning exercise** that puts key strategic considerations in a form that helps stakeholders understand and assess the range of options available, how and why they are interconnected, the pros and cons of different combinations of measures—including negative impacts—and how non-storage solutions may fit among the options or offer alternatives. Ultimately, it enables a more informed decision about which combinations of storage are worth exploring further and whether they should be implemented in parallel or in series.

The framework is organized in three stages: (1) a needs assessment to define the problem; (2) a definition of the system and potential solutions; and (3) a decision-making process that considers a range of scenarios and uncertainties. The first stage includes a definition of the development objectives and the related "water service requirements" to meet those objectives, and then characterizes the current water resources system (including storage) and other systems that may need to be considered (energy, agricultural markets, etc.). The second stage systematically identifies additional potential options (including options other than storage). It includes a range of storage options, from green to gray, small and large, and encourages consideration of many modalities of intervention, from rehabilitating existing storage, to retrofitting it for different uses, to reoperating storage, raising new storage, or engaging in other sectoral reforms. The final stage models how options, in different combinations or scenarios, would result in changed levels of services, and uses decision criteria to guide the choices for further study (figure ES.3).

The framework presented here is not only a technical review but is also ideally an opportunity to shift the conversation on freshwater storage so that it includes the more diverse group of stakeholders crowded in by a broader set of potential solutions. While the process outlined is fundamentally public sector-led, it recognizes the importance of the private sector and civil society in planning, developing, and operating water storage investments and highlights areas where they have specific roles to play. A multi-stakeholder planning process could be at the expense of expedient decisions, but such processes are proven to increase trust, stakeholder satisfaction, transparency, and performance in the water sector (Fox 2015; Water Witness 2020). These conditions enable greater ownership and buy-in from stakeholders, which could reduce delays in implementation. Each situation should be tailored

FIGURE ES.3 Integrated Storage Planning Framework Stages



Source: Original figure for this publication.

appropriately to the needs of the stakeholders to create sustainable and efficient storage capacity for both present and future needs. It is not meant to be exhaustive, but it provides tools and resources to arrive at better storage outcomes.

4. MAKING BETTER DECISIONS NOW

In a perfect world, well-developed regulatory and institutional frameworks that clearly lay out roles and responsibilities and set guidelines that support the assessment and implementation of water storage options would already exist. There would be regulatory frameworks that include protections for natural storage as well as for water towers, riparian areas, and critical groundwater infiltration areas, and sufficient quality data available upon which to base basin-level studies that scope options, risks, and opportunities, and sector plans informed by cross-sectoral linkages.

But this is not reality. In truth, the challenges in implementing an integrated problem-driven, systems approach to water storage planning are, in many ways, the same as those that encumber the implementation of IWRM. Despite growing awareness of IWRM principles among policy makers and water managers, the implementation of IWRM is progressing at only half the rate that is needed to achieve SDG target 6.5 (UN-Water 2021). The challenges extend to managing water storage in a more integrated way including lack of data, coordination challenges, misaligned incentives, institutional capacity issues, and funding.

Many planning and investment decisions are made—indeed, must be made—in the context of financial and human resource constraints and gaps in information. **The Integrated Storage Planning Framework will need to be implemented with imperfect information and with finite resources.** Water storage planners must strive to make better storage decisions while knowing that perfection is not attainable.

The framework is designed to be implementable even in the face of limitations that include:

- **Multi-Stakeholder Engagement and Coordination**
  - Beyond government, early integration of multi-stakeholder perspectives and knowledge in water storage planning is important—but it is not always hardwired into regulatory and institutional frameworks. As in the case of government agency coordination, ensuring the right composition of stakeholders from early on is vitally important. In many instances, this includes non-governmental stakeholders like civil society organizations (CSOs), private industry, and local communities.
  - **The problem-driven, systems approach explicitly includes stakeholder considerations at various levels of the process**. Early stages of the framework involve mapping the various stakeholders that may be affected by a set of water storage options and whose behavior will influence the performance of those options. The early mapping of stakeholders is neither costly nor time-consuming and provides a foundation for later stages, where more detailed information needs to be collected about stakeholder interests and capabilities. Having these considerations built in will help to screen out politically, environmentally, and socially infeasible options.

- **Regulatory Frameworks**
  - Many jurisdictions are missing or have outdated laws and regulations on water resources management and water storage. Existing laws and regulations may not reflect the actual level

of water resources development or may not be detailed enough to manage the trade-offs that inevitably emerge with ambitious development plans. Regulatory frameworks can support integrated planning if they emphasize the importance of basin-wide approaches, recognize the interdependence of built and natural systems, and include sustainable funding mechanisms for storage planning and management.

  - **The problem-driven, systems approach embeds these kinds of issues into the framework, so that if they are not explicitly provided for in the regulatory framework, they can still be considered in a systematic way**. Additionally, deficiencies in the regulatory framework may become apparent through the use of the planning framework and could be reflected in the regulatory reform process.

- **Private Sector Participation**
  - Private sector participation in water storage planning and management can come in many different forms—from management and operation contracts to the purchase of previously public assets to the provision of equity or loan financing. Private sector players may also have considerable expertise and access to technology that may be difficult to acquire in a fully public venture. Evidence from private sector participation around the world suggests that it increases operational efficiency, leads to higher-quality service provision, and supports the expansion of service delivery to underserved segments (Al-Madfaei n.d.).

- **Misaligned Incentives and Political Economy**
  - Where institutional arrangements are generally in keeping with international good practice, the political economy situation can lead to a mismatch between policy and implementation, making it harder to action integrated storage planning and management. The specific non-technical drivers of this mismatch will vary from place to place, but they generally reflect a shift to institutional rules that challenge pre-existing norms and behaviors around water management. Integrated storage planning and management, and IWRM, more generally, can be undermined, for example, by local political interference, privileged access of a select few, rent-seeking behavior, and power asymmetries between stakeholders. **Problem-driven approaches account for drivers of institutional non-performance by identifying the underlying problems as well as different stakeholder interests and capabilities**.

Implementing integrated storage planning will take time to be reflected in practice and in institutional frameworks for water management. Nevertheless, the problem-driven, systems approach can guide water managers through a step-by-step process that works around and through some of the institutional challenges. For those wanting to understand each phase of the framework in more detail, or to begin using it in practice, chapter 7 of this report elaborates on each stage and includes guiding questions when undertaking an options analysis and examples of technical tools and innovations to help in storage planning.

5. THE OPPORTUNITY: THINKING DIFFERENTLY

Across the water management continuum, from policy and key decision-makers in national governments to development and strategic planners in water and water-dependent sectors, to development practitioners who support project- and sector-level interventions, to the research community, our responsibilities and perspectives are manifold. Yet achieving resilient, sustainable storage solutions is predicated on a universal shift in thinking, a collective understanding of the new paradigm for water storage, and adoption of the key principles that characterize an integrated approach.

Developing an integrated approach requires a systems perspective. The hydrological system is the foundation for integrated storage planning and management, but there are also other environmental, social, and economic systems that need to be understood and addressed.

Thinking differently means making conceptual shifts (table ES.1) in how we think about water storage, toward an integrated approach that focuses on outcomes, integrating natural and built as a system, getting more from the current system, and managing risks through diversification.

Thinking differently requires not just deciding "What is the next investment to make?" but evaluating which combination of investments and policies offers the most robust and resilient system for long-term storage. This means considering a broad range of options, starting with understanding the current storage system. Being able to model the interactions and performance of the current storage system will help determine whether more storage services can be extracted from the current system, as well as what additional storage opportunities there might be. Critically, it also helps to identify the range of stakeholders that currently depend on the natural and built storage within the system, and who therefore need to be engaged in the process. Additional storage services can be gained from current storage or from adding new storage. Opportunities— known as "the 5 R's"—are outlined in table ES.2.

The benefits of a systems approach that includes the 5 R's—rehabilitating, reoperating, retrofitting, reforming institutions, and raising new—is exponentially more valuable than a siloed approach, culminating in wide-ranging insight into how optimized integrated storage solutions can help. These include managing water extremes, to treat floods as a water surplus that can be captured and stored for drier times (hydrological); saving on infrastructure that could be multipurpose (financial and economic), and serving the needs of several sets of stakeholders, or at least considering their needs in an integrated way (social). It can help reduce correlated risk, by diversifying types and location of water supply. Finally, it can enhance sustainability.

TABLE ES.1 Conceptual Shifts: An Integrated Approach to Thinking about Water Storage

TOPIC	FROM	TOWARDS
Defining success	Storage volumes	Storage outcomes—the services enabled by storage
Storage approaches	Built storage	Natural and built storage and their interactions
Storage management	Facility level	System level, working across institutions
Storage development	New development	Getting more from current—through retrofitting, reoperation, and rehabilitation—and developing new
Risk management	Infrastructure development	Diversification of storage types across storage systems

Source: Original to this publication.

TABLE ES.2 The 5 R's: Opportunities for Increasing Storage Services

Reoperation	The modification of storage operations for improved management (efficiency gains), which might include changing the timing of water releases from controllable infrastructure to increased benefits or adding additional benefit streams, such as flood control and minimizing storage losses from evaporation. This may also include managing for synergies between different types of storage or creating new connections between existing storage, so that they may be operated as part of a broader system.
Rehabilitation	The restoration of current storage—natural or built—to improve storage capacity or performance. Rehabilitation can extend the life of existing storage capacity and defer investment in new storage. Restoration of original capacity or slightly improved capacity could be achieved through addressing structural defects, sediment removal, increasing the flow rates of managed aquifer recharge sites, and environmental restoration of natural storage, among others.
Retrofitting	The upgrading or augmentation of capacity at existing storage facilities, and or enabling new uses of the facilities. This could be achieved through raising the height of dam walls or adding new hydromechanical or electromechanical equipment to serve different objectives or different customers to make overall gains in the value of storage services. Adding floating solar panels to existing hydroelectric projects or adding hydropower generation to irrigation projects are two examples.
Reform: Investing in institutions to manage storage better	In addition to physical investments in storage, policy makers need to invest in the institutions that are required to better plan and manage storage. This includes institutional capacities to: • Manage the data, modeling, and planning systems required to develop smarter storage. • Enable and incentivize integrated planning, development, and management at multiple scales across multiple stakeholders. • Mobilize the finance and financial incentives that enable storage to be prioritized, planned, and managed in the broader public interest. Policy and institutional approaches that manage water groundwater, improve the efficiency of services, price water services appropriately, and address social and environmental issues are all necessary complements to appropriate and sustained storage management. Land management, conservation, and protection measures are key requirements for maintaining or restoring natural infrastructure.
Raising New: Finding or developing additional storage	This would involve exploring the full range of available storage types: natural and built; surface and subsurface; large and small; and centralized and distributed. New storage might be built at a variety of scales or created in nature through different landscape management practices (e.g., accelerating aquifer recharge). New storage can also be designed to leverage or complement other parts of the system to make the whole greater than the sum of the parts.

Source: Original to this publication. The concept of the "5 R's" has been adapted from the Uncommon Dialogue on Hydropower, River Restoration, and Public Safety, Stanford Woods Institute for the Environment 2020.

6. RISING TO THE CHALLENGE: A CALL TO ACTION

This Call to Action summarizes the key conclusions and recommendations of this report around four themes:

A. ***Why** focus on water storage?*
B. ***What** do stakeholders need to understand to develop smarter approaches?*
C. ***Who** needs to be involved?*
D. ***How** can stakeholders approach storage more strategically?*

A. Why focus on water storage?

Water insecurity is growing around the world, influenced in some places by increasing demand, in others by degrading quality, and almost everywhere by climate change. Even countries with relatively temperate climates and large infrastructure endowments face increasing water insecurity, such as in Europe at the time of this report.

Smarter approaches to water storage will, inevitably, lie at the heart of responses to climate change. Beyond improving the availability of water during drier periods, mitigating the impacts of floods, and regulating flows for other purposes such as hydropower, storage is also a form of hydrological risk management. Families, farmers, businesses, and cities will invest more in their lives and livelihoods when they feel protected from water extremes.

As water storage grows in importance, current methods for developing and managing it are more obviously inadequate. Many approaches, in general, have been too fragmented and short term. The world today faces growing demand for water, increasing variability, and a growing water storage gap; yet current approaches to storage are no longer fit for purpose and do not add up to the comprehensive, sustainable, and integrated solutions that circumstances increasingly demand.

Call to Action Step 1: *Focus more, and more strategically, on water storage.*

B. What do stakeholders need to understand to develop smarter approaches?

While humans have been developing water storage systems for several millennia, nature has always provided the vast majority of freshwater storage. The first step, therefore, is identifying what storage we have, particularly the natural systems such as groundwater, wetlands, glaciers, and the soil moisture reserves on which people depend. Systematic mapping of natural and built storage on a basin-by-basin basis (as this is the practical operating scale of most storage systems) is needed, including data on volumes, reliability, and controllability of the water stored. Knowing what we have is the first step toward not taking it for granted and unnecessarily depleting it, as many parts of the world have been doing for several decades. It is also a necessity for informing future planning and investment decisions.

The second knowledge challenge is to understand storage as a system. Even very different types of storage are linked as part of a broader water cycle, meaning that they generally need to be developed and managed as an integrated system rather than as stand-alone facilities. Engineers have long understood that dams depend on their watersheds, but it is time to go much beyond this and understand not only the hydrological system but the broader social, economic, and environmental systems that interact with it, building upon decades of global experience with IWRM. The social and economic systems are the primary drivers of changing demand for storage services, while the broader environmental systems (biological, climatic, etc.) are both major users and shapers of water flows.

The third key knowledge challenge is assessing alternatives to storage. Storage challenges usually need to be assessed as part of a broader water resources context, and storage may not be the best solution to the problem at hand. Alternatives to storage could range from demand management to alternative supply measures for reducing scarcity; from zoning regulations to flood insurance for managing floods; and from alternative energy to alternative transport investments to storage's regulatory services. The important point is to consider alternative ways to deliver the service, not simply volumes of water.

The fourth big knowledge challenge is to develop and manage storage within a context of increasing uncertainty brought about by climate change. Managing storage as a system is a key step in the right direction since a diverse system will be more resilient to weather-related shocks than individual facilities. The fact that the past is no longer a reliable guide to the future has several ramifications, including a premium on the rapid collection and analysis of data to guide system understanding and management. But more broadly, climate change demands smarter approaches and tools to make long-term investments in natural and built infrastructure, and in the institutions to manage it. This report details a number of these tools, from decision-making under uncertainty to integrated modeling techniques, to make our processes "smarter."

> ***Call to Action Step 2:*** *Measure and model storage in an integrated way—natural and built, surface and sub-surface—to understand, develop, and manage storage as a system with long-term, sustainable, and resilient services as the end objective.*

C. Who needs to be involved?

Closing the water storage gap is a shared challenge. Faced with the growing risks of water insecurity around the world, global, national, and regional stakeholders can no longer focus on their own needs in isolation. A conceptual shift in thinking is required. **We all have a role to play.**

Governments and policy makers have a unique opportunity to lead by setting the criteria for success, advocating for an integrated, systemic approach to storage that begins with a rigorous definition of the water-related problems and prioritizing efficient solutions that benefit the largest range of stakeholders.

Utilities, businesses, irrigation schemes, hydroelectric producers, and other bulk users of water services have a key part in defining the problem through identifying their long-term water needs, including for storage services, as well as potential alternatives to them.

The social or environmental implications of different management approaches to built and natural storage (e.g., land-use restrictions) need to be carefully understood. Significant investments in storage may have significant trade-offs associated and different stakeholders with differing views on them. Storage services may be most efficiently provided through multipurpose infrastructure provided to multiple and sometimes competing stakeholders. All stakeholders, including those representing the environment, have a role to play in thinking through the trade-offs, as well as clarifying the value, and therefore the economic and financial sustainability, of future investments, as well as engaging in joint processes that help produce a shared understanding and more resilient, integrated services in the future.

Expertise and accountabilities vary significantly across the spectrum of those who work in water. Yet achieving change is predicated on a universal shift in thinking, a collective understanding of the new paradigm for water storage, and adoption of its key principles.

> ***Call to Action Step 3:*** *Engage all stakeholders to define the storage services needed (the "problem") and the trade-offs associated with future investments (the "solutions").*

D. How can stakeholders approach storage more strategically?

This report proposes an Integrated Storage Planning Framework intended to be helpful in developing more—and more sustainable and resilient—freshwater storage in the future.

Together, the framework's three-step process is designed to build the knowledge and the consensus required for investing in improved long-term water storage services. Critically, the framework includes ways to consider whether storage investments are really the best way to address water-related challenges, or whether alternatives should be considered.

At a practical level, this report identifies five major areas for investment in future storage systems (natural and built), summarized as the 5 R's: rehabilitating, reoperating, retrofitting, reforming institutions, and raising new. Many countries are likely to need to invest in all of these areas, including new institutional mechanisms that may be needed to undertake them at aquifer, basin, national, or transboundary levels. It also includes recommendations about how to approach mobilizing finance for storage, as well as to safeguard the economic returns over time through provisions for O&M.

> ***Call to Action Step 4:*** *Use an integrated planning methodology to identify and prioritize investments in both natural and built water storage and develop an institutional setup that can maintain and operate storage in the public interest for the long term.*

Water Storage: The Future Is Now

What the Future Has in Store: A New Paradigm for Water Storage is a progressively urgent appeal to multi-sector practitioners at every level, both public and private, to begin championing integrated smart water storage solutions that meet a range of human, economic, and environmental needs. Closing the water storage gap requires a spectrum of economic sectors and stakeholders to develop and drive multi-sectoral solutions that address solutions holistically, effectively, and efficiently. Done right, a new paradigm for water storage, backed by investment, will create a stronger foundation for sustainable development, climate action, and resilience, paying dividends for populations, economies, and the planet, through years and generations to come.

ABBREVIATIONS

5 R's	rehabilitating, retrofitting, reoperating, raising new, reform
AMI	area of maximum impact
ARA	active river area
CDMU	Central Dam Monitoring Unit
CGE	computable general equilibrium
CIA	cumulative impact assessment
CNFRC	California Nevada River Forecast Center
CO_2	carbon dioxide
CONAGUA	National Water Commission (*Comisión Nacional del Agua*)
CROPWAT	Crop Water and Irrigation Requirements Program
CSO	civil society organization
CW3E	Center for Western Weather and Water Extremes
CWC	Central Water Commission
DAD	Department of Agrarian Development
DGWR	Directorate General of Water Resources
DMU	Dam Monitoring Unit
DOISP	Dam Operational Improvement and Safety Project
DRIFT	Downstream Response to Imposed Flow Transformations
DRIP	Dam Rehabilitation and Improvement Project
DSC	Dam Safety Commission
DSP	Dam Safety Project
DSS	decision support system
DSU	Dam Safety Unit
DTF	Decision Tree Framework
DWS	Department of Water and Sanitation
EFA	environmental flow assessment
EFO	ensemble forecast operations
ESF	Environmental and Social Framework
ESIA	environmental and social impact assessment
ESMP	environmental and social management plan
ESS	Environmental and social standard
EU	European Union
FAMM	Monterrey Metropolitan Area Water Fund *(Fondo de Agua Metropolitano de Monterrey)*

FAO	Food and Agriculture Organization of the United Nations
FIRO	forecast-informed reservoir operations
FVA	full viability assessment
GCM	general circulation models
GDP	gross domestic product
GEF	Global Environment Facility
GGIS	Global Groundwater Information System
GHG	greenhouse gas
GIS	geographic information system
GRACE	Gravity Recovery and Climate Experiment
GRanD	Global Reservoir and Dam Database
HEC	Hydrologic Engineering Center
HEM	hydro-economic model
HMT	Hydro-Meteorological Testbed
HPP	hydropower plant
IBAT	Integrated Biodiversity Assessment Tool
ICOLD	International Commission on Large Dams
IDA	International Development Association
IDB	Inter-American Development Bank
IFC	International Finance Corporation
IGRAC	International Groundwater Assessment Center
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IUCN	International Union for the Conservation of Nature
IWRM	integrated water resources management
IWRSS	Integrated Water Resources Science and Services
IWMI	International Groundwater Assessment Center
IWS	investment in watershed services
MAR	managed aquifer recharge
MAWLR	Ministry of Agriculture, Water and Land Reform
MCDM	multi-criteria decision-making
MMA	Monterrey Metropolitan Area
MPWH	Ministry of Public Works and Housing
MRV	measurement, reporting, and verification
NBS	nature-based solutions
NDC	nationally determined contribution
NEAP	National Environmental Action Plan
NGO	nongovernmental organization
NOAA	National Oceanic and Atmospheric Administration
NRMC	Natural Resources Management Centre
O&M	operation and maintenance
OECD	Organisation for Economic Co-operation and Development

PES	payment for ecosystem services
PPIB	Private Power and Infrastructure Board
PPP	public-private partnership
PVA	preliminary viability assessment
RCP	Representative Concentration Pathway
RUSLE	Revised Universal Soil Loss Equation
SDG	Sustainable Development Goal
SEA	strategic environmental assessment
TNC	The Nature Conservancy
UNU-IWEH	United Nations University Institute for Water, Environment and Health
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
UTFI	Underground Taming of Floods for Irrigation
VEC	valued ecosystem component
WAPDA	Water and Power Development Authority
WCM	water control manual
WCP	water control plan
WCWSS	Western Cape Water Supply System
WMARS	Windhoek Managed Aquifer Recharge Scheme

UNITS

bm^3	billion cubic meter
GW	gigawatt
kl	kiloliter
km^3	cubic kilometer
m^3	cubic meter
MW	megawatt

**All dollar amounts are US dollars unless otherwise indicated.*


Banten, Indonesia. © Tom Fisk via Pexels.com

What the Future Has in Store: A New Paradigm for Water Storage **calls on all stakeholders to think differently, plan inclusively, and act systematically to address the water storage challenges of the coming century.**

MAIN REPORT

Part I

1 INTRODUCTION: THE IMPORTANCE OF WATER STORAGE

1.1 DEVELOPMENT AND CLIMATE RESILIENCE

1.1.1 Vital Social, Environmental, and Economic Resource

Freshwater sustains life and livelihoods. As it courses through our bodies, the environment, and our economies, water brings life, removes impurities, and transports everything from nutrients to commerce from place to place. The central challenges of water—too much, too little, too variable, and too neglected—are central challenges of our time.

Water crises are growing. The combination of growing demand and climate change are making water crises more common and more extreme. Droughts and floods compete for headlines, and the everyday lives of farmers, communities, cities, and countries become more complex and uncertain. Water and water-related disasters are often rated among the greatest risks facing modern societies (WEF 2022).

The poorest are often most vulnerable to water challenges. Poor people are often the least connected to reliable water supply and sanitation services and therefore are often the first affected by shifts in water availability. The poor are also often severely affected by floods, living in areas that lack adequate protection and drainage, including in degraded landscapes. Finally, to the extent that the rural poor rely on rainfed agriculture, their livelihoods are the first affected by rainfall variability and droughts. The effects of water scarcity on the poor can last for generations—studies show that drought conditions during a woman's early childhood can have a measurable effect on her children a generation later (Damania et al. 2017).

The environment is both a provider and user of water. Global and local water cycles are shaped by the environment. Freshwater ecosystems keep wildlife and vegetation alive; provide economically and commercially valuable services, including billions of dollars in water purification and fish capture (EEA 2021; Funge-Smith 2018), and play an important role in regulating the global climate, sequestering about 25–30 percent of the carbon contained in soils and terrestrial vegetation globally (Russi et al. 2013).

Water challenges are also economic challenges. Water is not only vital to human and ecosystem health but also to the health of our economies. There are several ways in which water quantity has significant economic impact:

» **Too little:** Water is a vital input to most economic production systems. Insufficient water could put a significant brake on economic growth around the world; as a result of water scarcity, some countries could experience up to a 6 percent reduction in growth. This in turn translates into a significant impact on jobs and livelihoods (World Bank 2016a).

» **Too much:** Floods are the most frequent hydro-climatic hazard, representing nearly half of all natural disasters between the years 2000 and 2019; during this period, 1.65 billion people were affected, with $651 billion in recorded losses (CRED and UNDRR 2020).

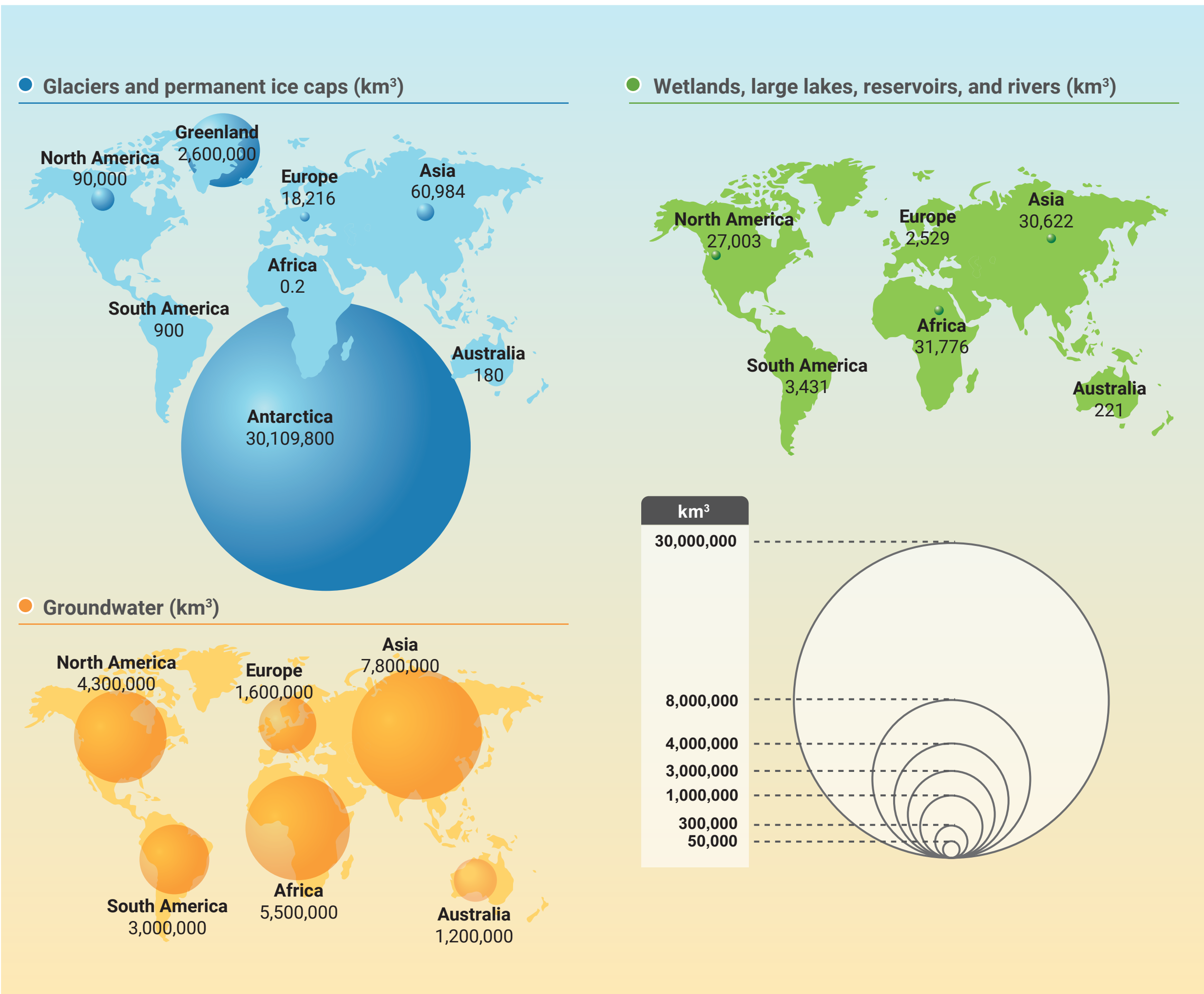
» **Too variable:** The relationship between rainfall and economic growth is particularly clear in agricultural areas where the link between the two is intuitive, but it has also been demonstrated to impact the manufacturing and services sectors (Damania, Desbureaux, and Zaveri 2019; Kotz, Levermann, and Wenz 2022). Farmers, firms, and service providers all need some degree of predictability to invest. Unreliable water supply also results in disruptions to economic activity, including in the informal sector (Islam 2019; Islam and Hyland 2019).

» **Too neglected.** Poor management of water resources hinders, and can even set backward, economic development. Poor water quality impacts economic growth; for example, the release of pollution upstream lowers economic growth in downstream areas, reducing gross domestic product (GDP) growth in downstream regions by up to a third (Damania et al. 2019). Access to groundwater—especially in deep aquifers and as aquifers are depleted, lowering water quality—can be costly and require large amount of energy for pumping.

Water is distributed unevenly around the world. The vast majority of the world's water is found in the world's oceans—only around 2.5 percent of water is fresh (USGS n.d., based on Shiklomanov 1993). The distribution of water across continents, countries, and basins varies significantly in quantity, quality, and seasonality. Map 1.1 summarizes the distribution of global freshwater resources by continent, demonstrating significant differences. In addition, water courses do not follow political boundaries, with nearly half of the rivers in the world spanning at least two countries, adding complications to managing water resources.

Water is also distributed unevenly within countries. Rainfall, surface, and groundwater can all vary considerably within countries. In the United States, for example, the wettest areas can receive roughly 100 times the rainfall that the driest areas receive. Huge variations in rainfall

MAP 1.1 Quantity and Distribution of Global Freshwater Resources, by Region



Source: GRID-Arendal 2009 (Cartographer: Philippe Rekacewicz). Licensed under CC-BY-NC-SA 3.0.

exist in many other countries, as varied as India, Colombia, Peru, and Papua New Guinea (Damania, Desbureaux, and Zaveri 2019). Ground and surface water is also geographically dispersed, leaving many countries relying on either natural systems—including rivers—or built infrastructure to move water from wetter to drier areas. More countries are now recognizing, though, that rivers are living ecosystems—some even with legal rights (Berge 2022)—which will have to be taken into consideration in the future in those countries when examining moving water within their borders.

1.1.2 Life Depends on Freshwater Storage

Storage increases the amount of water available for human, environmental, and economic use, reduces the impact of floods, and provides a variety of ancillary services by regulating water flows. Storage enables vital services such as water supply, sanitation, and irrigation, which in turn underpin human health, welfare, and food security. Water stored for hydropower not only produces clean energy directly but also stores energy for when it is most needed, allowing increased use of variable solar and wind energy. River or canal transportation also often relies on water storage to provide year-round accessibility for bulk goods carriers.

Nature has always provided the vast majority of freshwater storage. Nature stores water in a variety of ways. The rivers we rely on are rapidly filled through rainfall, but then also sustained through dry periods by the gradual release of water stored in the watersheds they flow through. The groundwater that more than one-third of the world's population rely on (Richts, Struckmeier, and Zaepke 2011) for daily survival is water stored underground by nature and replenished—or not—by complex ecological processes. Even today, over 99 percent of freshwater storage on earth is in nature (McCartney et al. 2022). The fact that it has always been there makes it somewhat invisible, or at the very least, taken for granted.

Nature also relies on water storage. The ecosystems around us have all evolved around the realities of natural storage. Ecosystems downstream of mountain glaciers or wetlands, for example, have developed as they have because "upstream nature" has stored and released water for "downstream nature" at different times of the year. If significant changes happen to upstream nature because of climate change or anthropogenic interventions, impacts on downstream nature are very likely.

Nature buffers societies against floods, slowing runoff and absorbing excess water into soils, vegetation, wetlands, and aquifers. The extent of nature's role in flood protection is becoming increasingly clear as we degrade it. Between 2000 and 2015, an estimated 255 million to 290 million people were directly affected by floods, which represents a 20 to 24 percent increase in the proportion of people exposed to flooding. In the future, floods will become even more common due to climate change, where projections suggest an additional 180 million people will be directly affected by flooding by 2030 (Tellman et al. 2021).

Human societies developed around natural storage. Reliability of freshwater was so catalytic to the rise of the earliest civilizations that they are often referred to as "river valley civilizations," including those that developed on the banks of the Euphrates, Indus, Nile, Tigris, and Yellow rivers. Other societies developed around readily accessible groundwater through springs or shallow wells. Early societies required reliable water supplies not only to drink and bathe but also to invest in early forms of agriculture and then manufacturing.

Humans began to supplement natural storage with dams as early as 3000 BCE. As the needs and ingenuity of early civilizations developed, they began to invest in ways to move beyond the constraints of natural storage and toward more regulation of the spatial and temporal variability of water, marking major episodes of development in Asia and Europe. Some 5,000 years later, cities as big as Las Vegas have developed in historically arid areas as large dams brought reliable water services to previously parched landscapes. For better or worse, large water infrastructure, including dams, has transformed the landscapes most people live in today.

Humans have also invested in storage at much smaller scales. Rice paddies, terracing, and other small structures have long been used by farmers to boost their productivity and extend their growing season. Rural and urban households capture water in tanks for domestic use to compensate for non-existent or unreliable services, or simply to take advantage of rainfall. Businesses of all sizes also develop and manage water storage for their needs.

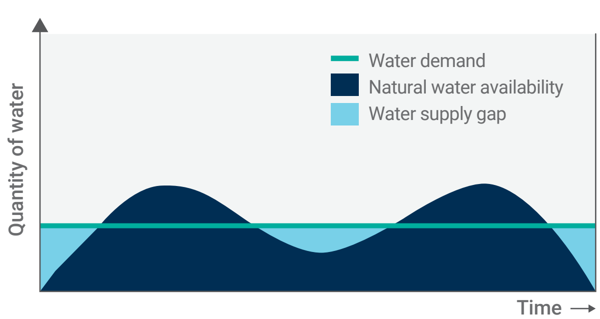
Today, our societies, economies, and the environment depend on a web of natural and built water storage. From the smallest household wells to giant reservoirs, mountain glaciers to coastal floodplains, water storage improves water availability, mitigates flooding, and otherwise enables a variety of other services—from hydropower to water transportation to leisure—that underpin much of modern life.

1.1.3 Climate Change Upends Our Relationship with Storage

Climate change is bringing profound changes to the water cycle, particularly through increasing the variability of precipitation. The Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report confirms that significant changes to the world's water cycle are already underway, and that these changes will likely grow in the future (IPCC 2021). While regional and local impacts will differ, climate change brings several challenges to storage; for example, as storage becomes more important to addressing growing variability, current storage becomes less effective as it was designed for historical conditions. Future storage becomes harder to plan.

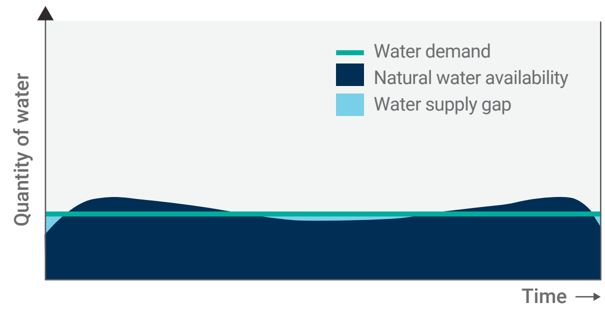
Storing water is a critical part of the societal response to hydrological variability and mounting water scarcity. Water demand is most often not aligned with natural water availability, especially in regions of the world where hydrological availability fluctuates widely between dry and wet seasons (figure 1.1). This creates gaps in water demand over time when water is either not available when needed or there is too much water proportionate to demand. By capturing some of the water instead of allowing it to flow naturally, water storage helps flatten

FIGURE 1.1 Water Demand vs. Natural Surface Water



Source: Original figure for this publication.

FIGURE 1.2 Surface Water Storage Impact



Source: Original figure for this publication.
Note: Surface water storage alters the temporal distribution of surface flows and makes water available at times and in quantities more closely matching water demands.

the curves and reduce the gaps in water demand, making water available over a longer period of time (figure 1.2). This supports efforts to improve the spatial and temporal distribution of freshwater, including reducing the risks associated with floods and droughts, to underpin basic service delivery and economic opportunities. It is important to recognize, however, that flattening the curve also has the potential to change the availability of water to downstream communities and ecosystems (including wetlands and lakes) that people depend on for their livelihoods.

1.1.4 Water Security Is More than Storage

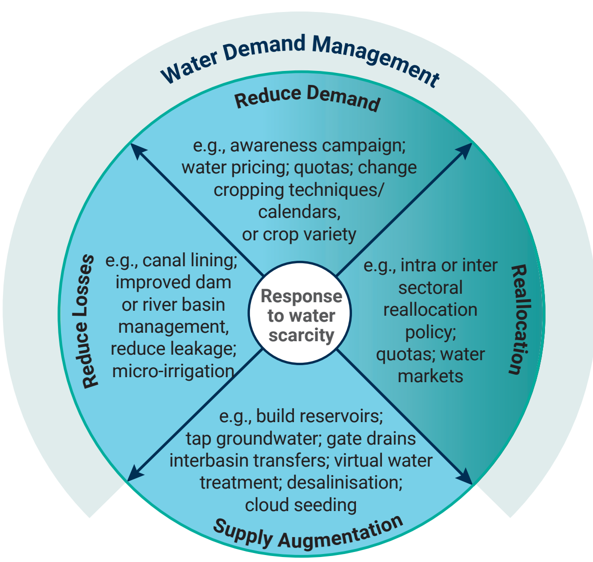
Storage is best understood as one of several elements that can contribute to long-term water security. Storing water does not "make" new water but regulates it in ways that shift its prevalence across space and time. Water storage investments, by making the temporal and spatial distribution of water more favorable, can also have the unintended effect of creating new water demands or perpetuating perceptions of abundance, which may lead to unsustainable resource exploitation. Investing in and managing water storage must, therefore, be done in a way that does not undermine the role it plays in improving water security.

More storage is not always the answer—and can be part of the problem. While storage is vitally important to current and future water management, it is only one part of the broader integrated water resources management (IWRM) puzzle. Increasing storage may not be the best approach to addressing water resource challenges in many circumstances, and the dynamic relationship between demand for water and its easy availability—such as through large new storage projects—may in fact accelerate the use of water, especially if investments in water storage are made without having appropriate policies and institutional arrangements in place. The right balance between investing in storage versus managing demand (including through better valuation and pricing of water), water trade-offs, and a variety of other supply-side approaches (figure 1.3) will be dependent on local circumstances, as is explored throughout this report.

1.1.5 Services of Storage

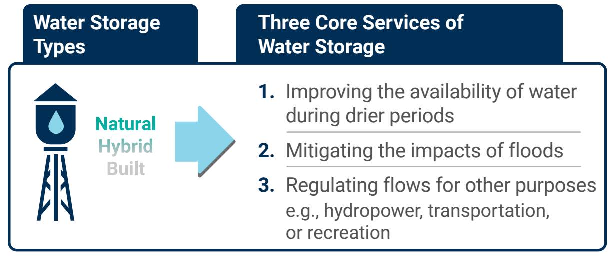
Water storage provides three broad services: (a) improving the availability of water during drier periods, (b) mitigating the impacts of floods, and (c) regulating flows for other purposes, such as hydropower, transportation, or recreation (figure 1.4). Each of these core services may be derived from multiple forms of storage, and all three are broadly trying to ensure that water is available in the right amount, in the right place, and at the right time. Each of these direct services also provides a more indirect risk mitigation or management service.

FIGURE 1.3 Response Options to Water Scarcity: Supply and Demand Management



Source: Adapted from Molle 2010.

FIGURE 1.4 Water Storage Types and Core Services



Source: Original figure for this publication.

Improving the availability of water. Storing water is particularly important where the natural variation in precipitation is high. Most locations on earth experience a seasonal rainfall pattern, occurring as a single wet and dry season or multiple wet and dry seasons over the course of a year. In addition to regular dry seasons, there are cyclical droughts that can last months or even years. Over the last 20 years, droughts affected 1.43 billion people and cost $128 billion in recorded losses, which is known to be an underestimate due to incomplete reporting, particularly in Africa, the region hardest hit by droughts (CRED and UNDRR 2020). Water storage is a mechanism to bridge water availability during dry seasons and droughts, making water services more reliable and increasing water security opportunities for economic development.

Storage helps manage flood impacts. Storage can capture flood peaks, slowing or even stopping the flow of flood waters and thereby reducing the impacts of floods downstream. Where flood waters are redirected into groundwater, reservoirs, or other controllable forms of storage, the same water can then be used for times when rainfall and river flow are lessened (Pavelic 2020).

Storage is a tool for regulating water levels to suit a specific economic or societal purpose, such as maintaining navigation, recreation, or the ability to produce hydropower. Upstream storage on a river can be used to regulate water levels downstream to allow sufficient clearance for passage of vessels. Hydropower can benefit from storage in several ways: through increased water availability during dry periods; through higher water levels for increased power production; and for the regulation of downstream releases for environmental reasons. Storage can support reservoir or downstream water levels needed for boating (including whitewater rafting), fishing, swimming, or other recreational purposes. Finally, surface water storage can also be used strategically to enhance groundwater recharge to curb saline intrusion or for other purposes.

Storage is a form of hydrological risk management. The amount of water storage a society needs is influenced by its tolerance for risk, which is related to the value of the goods or services threatened by hydrological extremes in the absence of sufficient storage, as well as the non-market value placed on life and health. Floods, for example, can be extremely destructive and can cause damage to property, life, and livelihoods. Water storage is, therefore, an investment in risk reduction for drought or floods, and ultimately in resilience to natural disasters and climate change.

1.1.6 Needs Differ Around the World

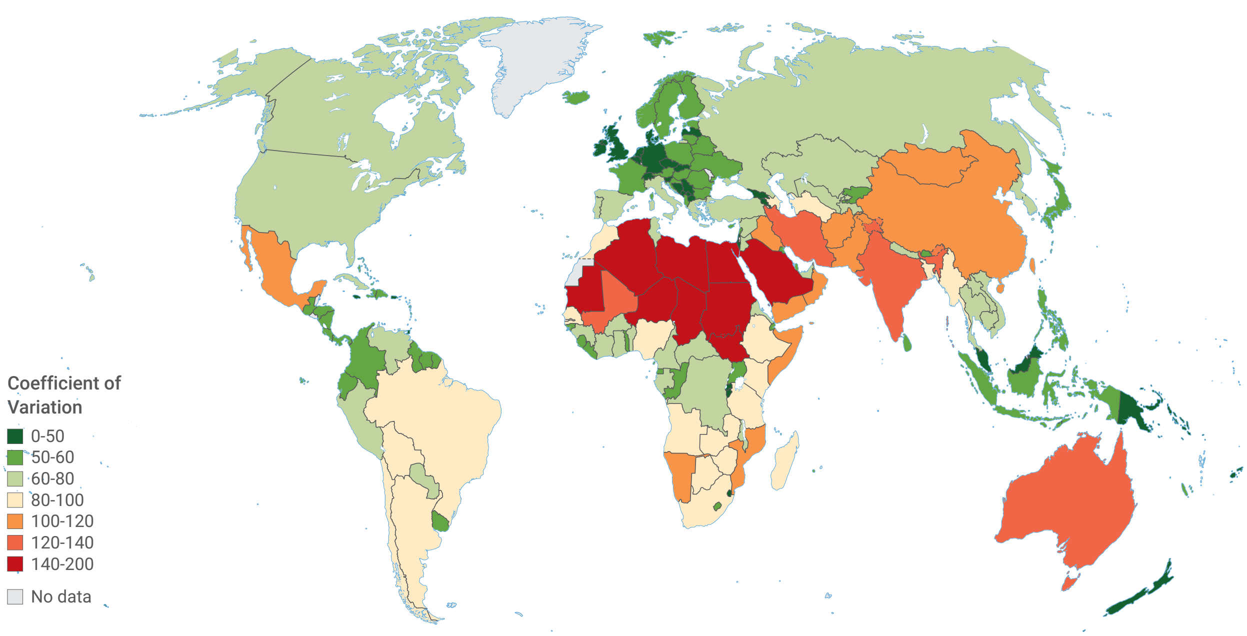
Water storage needs are influenced primarily by current circumstances, future needs, and tolerance for risk. Current circumstances include the water endowment, variability in precipitation within and across years (map 1.2) (Fader et al. 2016), the amount of natural storage that is practically available, and the status of built storage. Current circumstances also include levels of economic development, and the associated public and private resources needed to develop storage. Future needs are primarily influenced by changes in variability (i.e., climate change), growth in demand, and rates of sedimentation, while tolerance for risk pertains to the socially acceptable levels of flood, drought, and other related risks. A country with rainfall that is relatively well-distributed, groundwater that is located close to demand centers, and good infrastructure begins in a very different place than a country with highly seasonal rainfall, limited groundwater, and significant infrastructure deficit.

1.2 OUR FUTURE UNDER THREAT

1.2.1 Growing Demand for Freshwater

In the last century, global demand for freshwater use has increased by a factor of six. This demand continues to grow at approximately 1 percent per year, roughly matching the global population growth rate (UNESCO 2021).[1] The

MAP 1.2 Coefficient of Variation of Mean Monthly Precipitation



Source: Adapted from Fader et al. 2016.
Note: As average for the period 2000–05. Coefficients of variation were calculated by dividing the standard deviation of monthly rainfall by the annual mean of monthly rainfall.

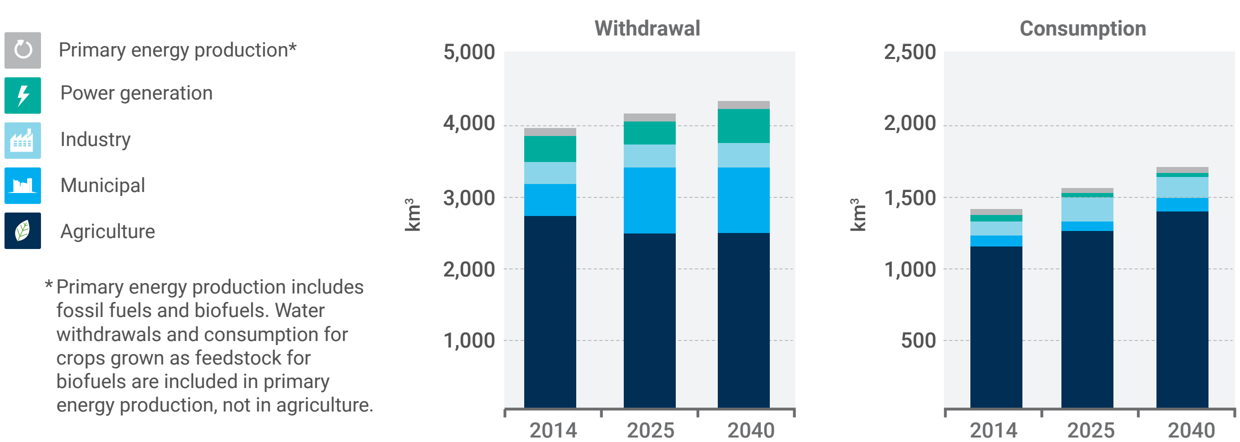
global population has grown from 1 billion in 1800 to 7.8 billion in 2020, and estimates put it at 8.5 billion by 2030, 9.7 billion by 2050, and 10.8 billion by 2100. Until 2100, more than 60 percent of the world's population growth will be in Sub-Saharan Africa and South Asia; in 2100, these regions together are expected to account for 55 percent of the world's population.[2] In member states of the Organisation for Economic Co-operation and Development (OECD), where per capita water use rates tend to be highest in the world, the increase in per capita water use has tapered. However, water use continues to rise in emerging economies and middle, and lower-income countries due to population growth, economic development, and shifting consumption patterns. At the current rate of change, by 2050, there will be a 20 to 30 percent increase in water use as compared to today (UNESCO 2021).

Development is increasing water demand, while rapid urbanization and shifting demographic patterns are shifting demand centers. In 2018, about 55 percent of the world's population lived in urban settlements. By 2050, this number is expected to grow to 68 percent, concentrating demand for water services. During that same period, urban water demand is expected to rise between 50 and 80 percent (Garrick et al. 2019) due to population growth in urban areas, combined with the fact that per capita water use among urban dwellers is higher because of a higher standard of living. Compounding the problem, the urban population facing water scarcity is also expected to rise from 933 million in 2016 to between 1.7 billion and 2.4 billion in 2050 (He et al. 2021).

Higher and more concentrated demands for water services will translate into significant increases in freshwater needs, as well as a need for water storage (figure 1.5). By 2050, the world will need to grow 60 percent more food to keep up with population growth, which, under a business-as-usual scenario, is estimated to require a 50 percent increase in irrigated food production while only an additional 10 percent in water withdrawals is estimated to be available (He et al. 2021). Expected improvements in water use efficiency and increases in reuse will be important in slowing the growth in freshwater withdrawals, as will decoupling economic growth from requisite growth in water use, especially in the agriculture sector, but the trend toward increased water stress continues. Already, more than 2 billion people live in countries that are water stressed (United Nations 2018), and an estimated 4 billion people live in areas that experience severe physical water scarcity for at least one month per year (Mekonnen and Hoekstra 2016).

Climate mitigation efforts mean that demand for energy-related water storage is expected to increase. Hydropower will likely play a key role in climate change mitigation efforts, and demand for water storage for hydropower is expected to increase. The International Renewable Energy Agency (IRENA) estimates that 1,300 GW of new capacity is needed to decarbonize the energy sector, meaning that investment in hydropower production will need to double (IRENA 2021). In addition to generating electricity, hydropower can provide energy storage and grid-balancing services, which are key to enabling the scaling up of other

FIGURE 1.5 Global Water Demand by 2040



Source: Adapted from United Nations 2018.

more variable renewable energy sources such as solar and wind. Demand for hydropower pumped storage is also expected to increase in many markets given its ability to store large amounts of surplus or cheap energy and release it on demand. Sixty-two percent of the Nationally Determined Contributions (NDCs), the plans through which countries disclose their plans to meet the climate commitments set at the Paris United Nations Framework Convention on Climate Change Conference of the Parties, include water storage as a mitigation measure. As such, energy-related water consumption could increase by nearly 60 percent between 2014 and 2040 (IEA 2017). Water consumption related to the transition to clean energy will depend on which clean energies are employed, as some, such as solar photovoltaic (including floating solar panels, wind, and run-of-river hydropower), consume relatively smaller amounts of water than biomass and some types of reservoir hydropower that can have higher water consumption due to evaporation. Water use for each source of energy can vary greatly between countries, however, due to different geographic conditions (Jin et al. 2019).

How we operate storage and manage our water may need to change to minimize greenhouse gas (GHG) emissions, translating into further changes in water demand. Our understanding of carbon and methane emissions from reservoirs is still evolving, and more research and monitoring are needed of storage operated for reduction of GHG emissions from drawdown areas (Harrison, Prairie Mercier-Blais, and Soued 2020). Rice uses 40 percent of all irrigation water worldwide (Bouman, Lampayan, and Tuong 2007). Paddy rice production accounts for 11 percent of all anthropogenic methane emissions and 1.5 percent of global GHG (IPCC 2019). There are ways in which rice production can be altered to decrease methane releases, which involve alternating between wetting and drying techniques in rice fields (World Bank 2020), although work is needed to mainstream alternative practices for GHG reduction throughout agriculture. However, this may mean a significant shift in where and when water is needed for agriculture in certain parts of the world, which could also influence other water users, depending on how water storage and supply systems are constructed.

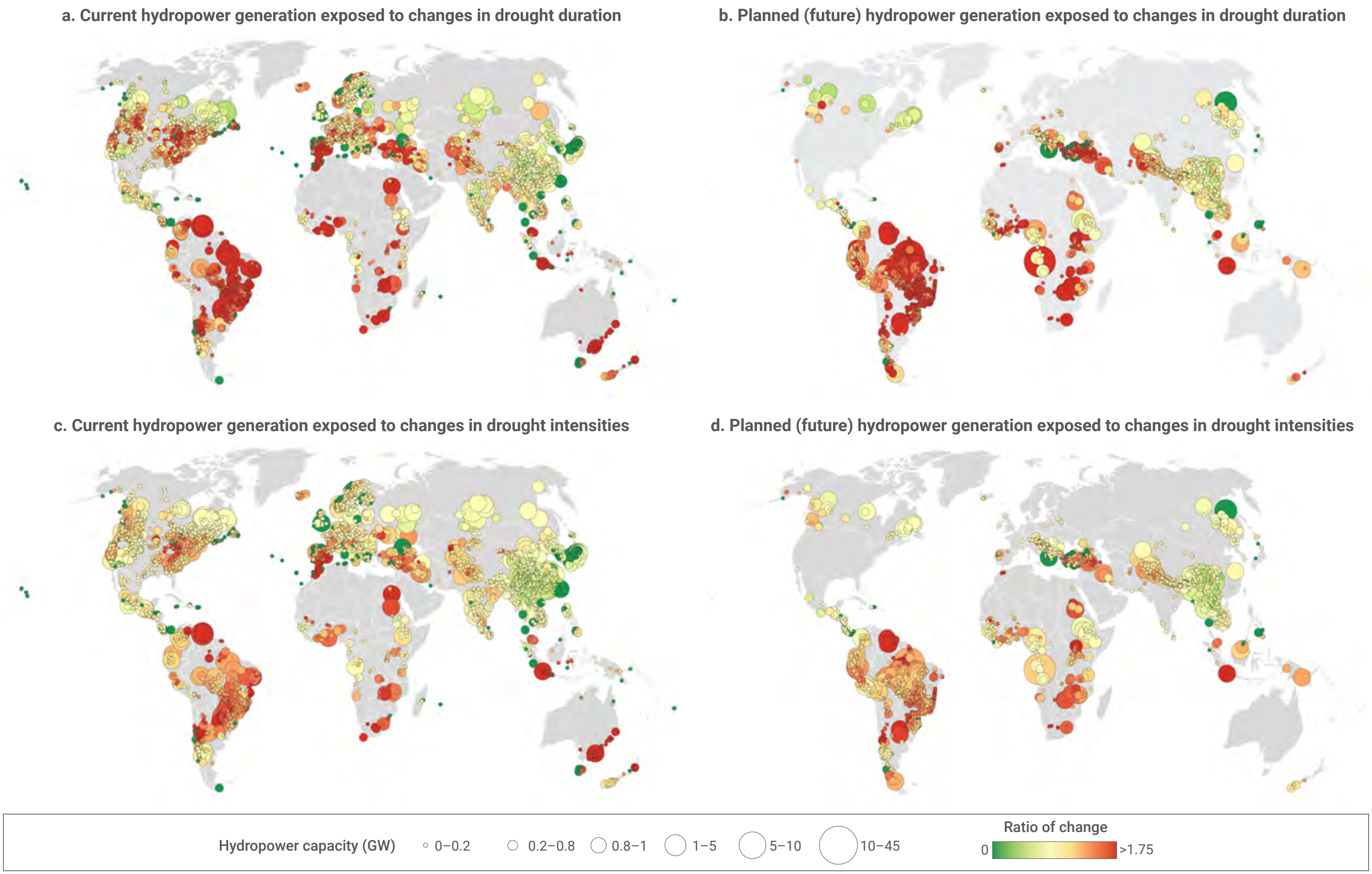
1.2.2 Growing Uncertainty of Supply

Climate change is altering the distribution of water across space and time, increasing uncertainty around rainfall, river flows, and groundwater recharge. IPCC's Sixth Assessment Report states that, without significant reductions in GHG emissions, the water cycle will undergo substantial changes at global and regional scales (IPCC 2021). This will include increases in hydrological variability and extremes in most regions of the world. Many areas are projected to have an increase in evapotranspiration, resulting in a decrease in soil moisture, and will be subject to increasing drought frequency and severity. Precipitation is projected to increase in some parts of the world and decrease in others, yet precipitation that comes with extratropical storms and atmospheric rivers will likely increase in most regions. Ultimately, "*natural climate variability will continue to be a major source of uncertainty in near-term (2021-2040) water cycle projections*." (Douville et al. 2021).

Climate change will increase hydrological variability, shifting "normal" rainfall patterns into new unknowns, increasing frequency and intensity of floods and droughts, and increasing the need for storage in some areas. A recent study estimated an increase in variation in seasonal precipitation, especially in regions that already experience great seasonal variation in precipitation (Konapala et al. 2020). Current management tools and coping mechanisms, including our built infrastructure, have been designed around the hydrological reality of the past—and may not continue to deliver with the same level of reliability. In some areas of the world, more storage will be needed to deliver water with the same level of reliability provided by current storage systems; this pattern will hold in locations where climate change will increase the variability of rainfall more than the mean annual rainfall will increase (Siam and Eltahir 2017). For hydropower, the projected changes in precipitation and temperature mean greater fluctuations in generation output (map 1.3) (Paltán et al. 2021). Limited local capacity to manage shrinking reservoirs and lack of adaptation readiness are expected to exacerbate the situation.

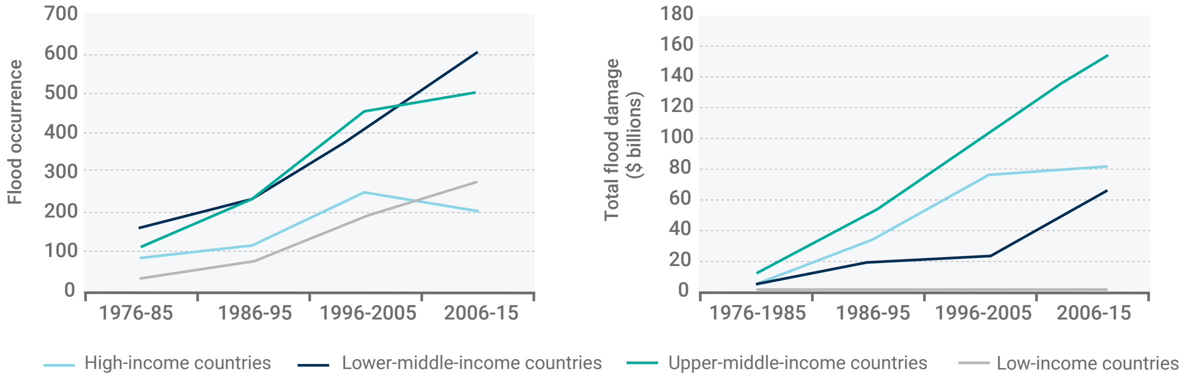
Water storage will be a critical adaptation measure to combat changes in precipitation and increasing hydrological variability. The frequency of severe flood events and associated economic losses have rapidly increased in recent years (figure 1.6). The IPCC states in its most recent report that continued global warming will "*further intensify the global water cycle, including its variability, global monsoon precipitation and the severity of wet and dry events*" (IPCC 2021). Hydro and climate variability may

MAP 1.3 Exposure of Hydropower Generation Capacity to Changes in Drought Durations and Intensities



Source: Adapted from Paltán et al. 2021.
Note: Exposed hydropower generation capacity to changes in drought durations and intensities at 1.5°C, relative to the historical baseline, for current and planned hydropower projects.

FIGURE 1.6 Flood Occurrence and Economic Damage Over Time



Source: Adapted from UN-Water 2018.
Note: Flood occurrence and flood damage figures are based on reported disaster events.

cause increases in internal migration of up to 216 million people (Clement et al. 2021). Without additional flood protection measures, the projected number of people annually affected by river floods could rise to 110 million by 2050 (Ligtvoet et al. 2018) due to population growth, migration, and climate change. In terms of drought, by 2050, one in seven people working in agriculture could be exposed to a severe level of drought (Bowcott et al. 2021). By mid-century, with increased drought, the global occurrence of forest fires could increase by 57 percent (UNEP and GRID Arendal 2022). As floods and droughts become more extreme and hydrological variability increases due to climate change, adaptation to maintain and improve water security becomes more crucial. Water storage plays a key role in alleviating hydrological variability. Areas with the most irrigation coverage experience three times less out-migration than the areas with the lowest levels of irrigation in the time of drought (Zaveri et al. 2021).

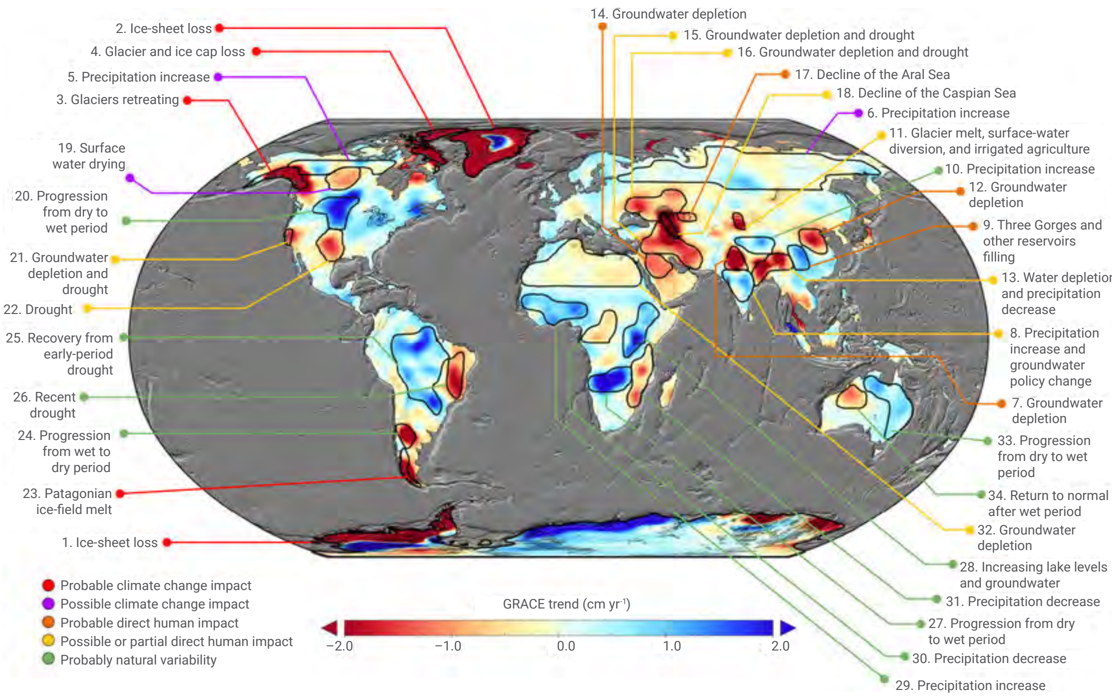
1.2.3 Decreasing Net Storage

The natural water storage systems people historically rely on—glaciers, wetlands, soil moisture—are in decline or being disrupted. From 2002 to 2016, 23 of 34 regions in a global study demonstrated a negative change in terrestrial water storage (map 1.4) (Rodell et al. 2018). That most of these areas are found in ice-covered regions and the mid-latitudes is concordant with the IPCC's findings that precipitation will increase in the low and high latitudes and decrease in the mid-latitudes (IPCC 2013). Glaciers are shrinking and snow cover is lost due to increased temperatures, and wetlands are disappearing because of climate change, land development, agriculture, urbanization, and pollution. Soil moisture is also decreasing through evapotranspiration as temperatures rise and groundwater reserves are being depleted through overexploitation and contamination.

Total built storage has increased significantly over the last century but not necessarily on a per capita basis. The rate at which new reservoir storage has been added since about 1980 has declined, and there is increasing loss of storage space to reservoir sedimentation because of nonexistent or ineffective reservoir sediment management. Figure 1.7 shows that total net reservoir storage space, after accounting for storage loss due to sedimentation, has decreased since about 2000, while global storage space per capita has decreased since about 1980. The current per capita net reservoir storage space roughly equals what it was in 1965 (Kamphuis and Meerse 2017). However, our demands for water storage are higher than they were in 1965. Implementing reservoir sediment management techniques to preserve reservoir storage space is critically important.

Over the last 50 years, natural storage losses are significantly larger than built storage gains, with a net freshwater storage loss of approximately 27,000 bm³, or approximately 3 percent of all "operational" freshwater storage. The volumes and percentage change of storage by type are summarized in figure 1.8 (McCartney et al. 2022). This global pattern may play out very differently at the local level. Ice sheet storage losses, for example, are not relevant to most local water storage challenges, and the major glacier and groundwater storage losses are concentrated in certain areas of the world. However, the breadth

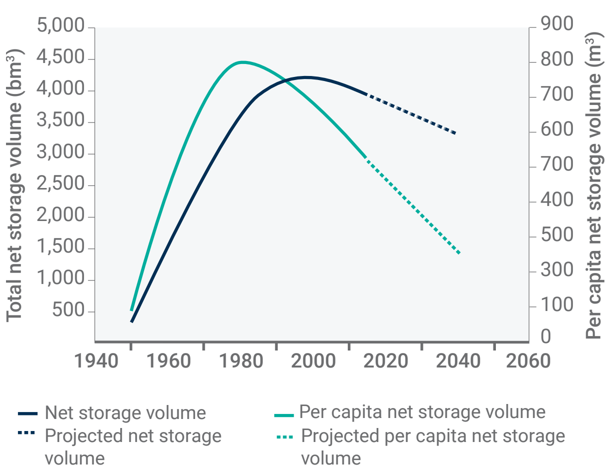
MAP 1.4 Global Terrestrial Water Trends



Source: Reprinted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Rodell, M. et al. "Emerging Trends in Global Freshwater Availability." *Nature* 557, 651–59. ©2018.
Note: Data was obtained through GRACE satellite observations from 2002 to 2016 and illustrates water trend changes in centimeters per year.

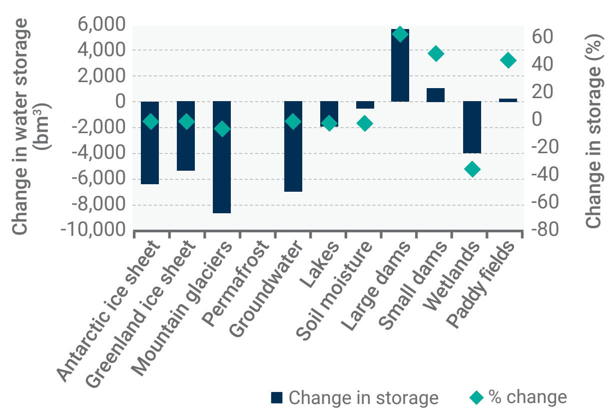
and volume of natural storage losses, and the underlying reasons described in this report, are an important warning to water planners around the world that we should not be taking such storage for granted in the future. For those in areas with groundwater and glacier loss, it presents an immediate problem.

FIGURE 1.7 Net Global Reservoir Storage Volume



Source: Annandale, Morris, and Karki 2016.
Note: Net global reservoir storage volume, accounting for storage loss from reservoir sedimentation.

FIGURE 1.8 Changes in Water Storage, by Type, 1970–2020



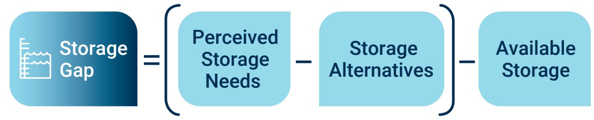
Source: Adapted from McCartney et al. 2022.

1.2.4 A Growing Water Storage Gap

A *water storage gap* is defined as the difference between the amount of water storage needed and the amount of operational storage (natural and built) that exists for a given time and place (GWP and IWMI 2021). Ultimately, all water storage gaps are local, measured in simplest terms by supply versus demand. However, quantifying the gap for any given location is a complex matrix requiring an aggregation of a variety of factors on both the demand and supply-side, as well as an evaluation of supply alternatives. In any system, storage demands occur at varying scales, times, and volumes, with requirements related to reliability, vulnerability, resilience, and control. On the supply side, availability depends on natural, built, and hybrid storage, with combinations offering a variety of advantages in terms of scale, timing, volume, and service.

In designing holistic, strategic responses to a storage gap, decision-makers must be aware that storage can be supplemented by demand management or supply augmentation. As a result, the size of the storage gap may differ significantly over time even if the amount of storage stays the same. As shown in figure 1.9, perceived storage needs may be reduced by storage alternatives such as demand reduction measures (leakage reduction or demand-control pricing) and alternative supply options (desalination or treated wastewater reuse).

FIGURE 1.9 Water Storage Gap

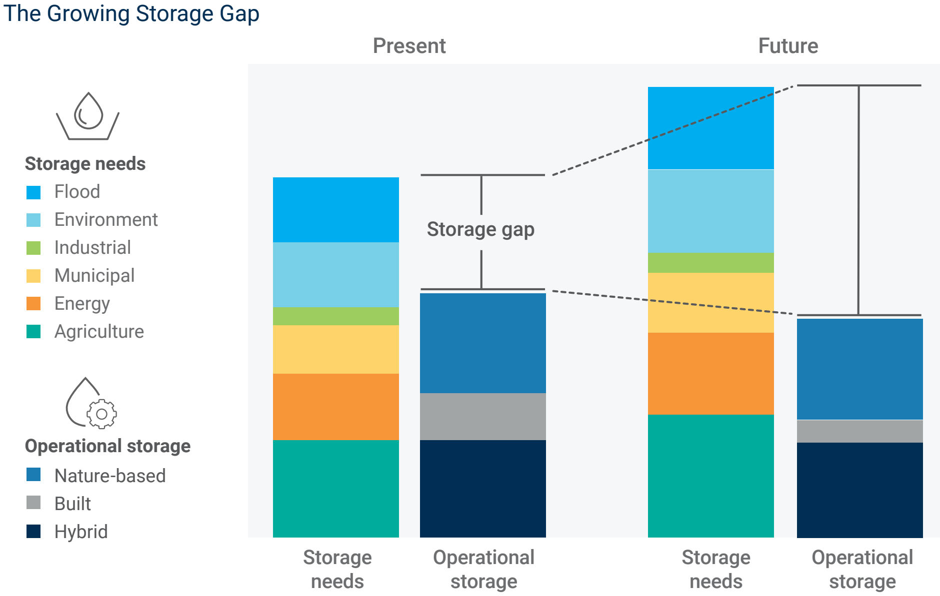


Source: Original figure for this publication.

Global trends suggest a growing storage gap. Over the last 50 years, the global population more than doubled, water variability grew, and freshwater storage declined (McCartney et al. 2022). Regional predictions show that terrestrial water storage will decrease in several parts of the world under climate change: By the mid- (2030–59) and late (2070–99) twenty-first century, terrestrial water storage is projected to substantially decline in the majority of the Southern Hemisphere, United States, most of Europe, and the Mediterranean, but increase in eastern Africa, South Asia, and northern high latitudes, especially northern Asia (Pokhrel et al. 2021). Figure 1.10 illustrates how these trends point to a larger gap between global needs and operational storage in the future (GWP and IWMI 2021).

How the global storage gap will translate in specific locations depends on the country or local conditions. Some countries may experience less pressure while others already have significant water storage gaps that will likely worsen over time. Some locations may require only slight changes to the operation of existing water storage

FIGURE 1.10 The Growing Storage Gap



Source: Adapted from GWP and IWMI 2021.
Note: Amounts of storage needed and operational storage are stylized estimates.

infrastructure that is already embedded in a solid, holistic water resources management institutional setup to optimize their operation. Others may require a more comprehensive intervention to expand the scale of water storage available, necessitating more storage or more efficient use and management of storage, as well as other water resources management measures.

Demand for additional storage may be direct or indirect, have varying levels of predictability, and stem from the variety of services that storage supports. Direct users of water storage services, such as water utilities or irrigators, have the incentive to plan for their future needs. Indirect users, such as urban households or businesses, have less incentive (and less control). Significant uncertainties can also make planning for storage more complex, including environmental and climate change, and societal shifts ranging from changing diets to migration, displacement, and economic change. Table 1.1 provides some examples of demand drivers and sources of uncertainty for freshwater storage demand.

The storage gap is further complicated by the transboundary nature of water, as well as institutional divisions. Of the world's transboundary rivers, around two-thirds do not have institutional structures governing their planning and use, making joint coordination difficult (United Nations 2018). This institutional issue is even more protracted for transboundary groundwater systems where only five transboundary aquifers had a cooperative management framework in place (Burchi 2018). Within countries, public responsibility for storage planning and management is usually divided across sectoral ministries (from agriculture, energy, environment, water supply and water resources) and administrative levels of government, with responsibility also resting with dam owners and operators.

While storage gaps are likely common in many parts of the world, their distribution and severity are largely unmeasured. The lack of systematic data on storage gaps is likely partly related to a more general lack of specific water data in many places but is also likely because many stakeholders do not yet see the value of measuring their storage gap at an aggregate level, which in turn is related to the way that storage development has been approached in the past. As the next section outlines, it is time to think differently and develop smarter approaches to water storage.

TABLE 1.1 Drivers of Demand and Demand Uncertainty

SERVICE	DIRECT DEMAND	SOURCES OF UNCERTAINTY
Increasing water availability	• Bulk water planning for urban utilities • Expanding irrigation needs • Small-scale rural water supply • Industrial water user needs such as energy utilities, mines, manufacturing, etc.	• Sudden demographic shifts or population movement, such as through conflict • Changes in consumer sentiment, including willingness to reduce consumption, changes in diets, or resistance to infrastructure development • Technologies that significantly improve water use efficiency • Upstream investments that change downstream water flows, including transboundary impacts • Climate change
Flood protection	• Residents and investors in areas of known flood risk • Governments, including urban or national planners • Insurance providers and financial sector more broadly	• Climate change impacts on flood extent and duration • Accuracy of flood risk maps based on historical hydrology • Willingness to pay for flood mitigation measures • Changes to upstream land use, land cover • Urban subsidence
Water-level regulation	• Hydropower and pumped storage systems developers • Shipping/logistics managers, passengers benefitting from inland water transport • Tourism and leisure service providers	• Demand shocks for water-based transportation • Extent to which climate change accelerates hydropower investment as a complement to other renewables or reduces hydropower investment due to water availability risks • Changes to water quality affects demand for leisure services

Source: Original to this publication.

1.3 THE WORLD NEEDS SMARTER APPROACHES

Current approaches to freshwater storage development and management are inadequate for the twenty-first-century challenges we face. The problem with freshwater storage today is not only that storage gaps are growing but also that the current paradigm for closing the gap is no longer fit-for-purpose, and in some cases, is counterproductive. Current approaches are often fragmented, overly reliant on built infrastructure, insufficiently focused on the ultimate service, and inadequately maintained and operated, among other challenges. Table 1.2 outlines dimensions of a paradigm shift that will be required for effective freshwater storage in the coming decades.

Within the shifts described, principles for better storage planning can be applied. For example, the paradigm shift allows for more efficiency in obtaining services from storage, recognizing that funding and investment resources are limited for meeting the storage gap. Further, the paradigm shift will need to allow us to look at equity and distributional impacts of storage, or lack thereof, including on marginalized populations, the environment, and future generations.

We need a diagnostic process to measure the gap in water services, and to work out whether it's best filled through demand—side measures, alternative supply, or storage—and if storage, what type(s) and developed in what sequence. If additional storage is needed, the gap might be closed through rehabilitating, reoperating, or repurposing current storage, "raising" new storage, and through reforming institutional management practices, what from here on are referred to as the "5 R's" of water storage.[3]

1.3.1 A Systems Perspective

A systems approach to planning and managing storage is needed to integrate the hydrology, socioeconomic factors, and institutional framework of a geographic area. A proper understanding of the hydrological system is the starting point for a systems approach, and, in particular, to allow an integrated perspective on natural and built infrastructure. A systems approach moves beyond the current fragmented approach to water storage development and management. There is a tendency to approach development and management of water storage—whether natural or built, surface or sub-surface, small or large—as separate units rather than an integrated system, leading to a variety of negative consequences.

TABLE 1.2 A Needed Paradigm Shift

RELATED TO	FROM	TOWARD
Defining success	Success measured by storage volumes	Success measured by storage outcomes: the services enabled by storage
Storage technologies	A focus on built storage (and, more recently, advocacy for nature-based services)	A focus on natural and built storage and their interdependencies on a hydrological system of storage
Planning and development approach	A focus on the next investment for the stakeholder with the presenting problem	A focus on long-term aggregate system development for all relevant stakeholders, including alternative supply and demand management. This includes a basin perspective in siting new infrastructure, considering hydrological, environmental, and social factors, to minimize and mitigate impacts
Life-cycle approach	A focus on storage development, with mixed performance on long-term maintenance, rehabilitation, etc.	Emphasis on maintaining and extending the life of natural and built systems—from wetland protection to sediment management—in addition to new development designed for long-term, sustainable use
Operations approach	Managing storage on a facility-by-facility basis, with some examples of multiple facility coordination	Managing storage as an integrated system, including both natural and built storage, to achieve system optimization

Source: Original to this publication.

Storing water and managing storage are key elements of water security but must be part of broader integrated water management, service planning, and implementation. Storage is one of several elements that can contribute to long-term water security, including managing water demand—for example, through better valuation and pricing of water—and decoupling economic development from requisite increases in water demand, and with broader natural resource depletion. Where water storage is part of the solution, it is essential to look at a holistic range of options, including non-water-dependent options where appropriate.

These challenges, as well as examples of opportunities to address them, are further explored in this report. Understanding the current status of the world's water stores and adopting more integrated, systems-based approaches will help us make better decisions around managing existing storage and investing in new storage. These combined resources are intended to help advance sustainable development and management of water storage worldwide in order to build water security. Toward this, this study seeks to outline a framework for integrated management of water storage to better equip water managers and policy makers in developing and operating water storage in the twenty-first century and beyond. This study proposes a step-by-step approach, using a problem-oriented lens, to guide the planning and operation of a resilient water storage management system. Finally, this report provides examples of water storage solutions from around the world to help shed light on and support the scale up of successful experiences (see case studies, chapter 8).

ENDNOTES

1 World Bank Database. Population growth (annual percentage). Accessed October 18, 2021. https://data.worldbank.org/indicator.

2 United Nations, Department of Economic and Social Affairs, Population Division (2019) database. World Population Prospects 2019. Accessed October 17, 2021. https://population.un.org/wpp/.

3 The concept of the "5 R's" has been adapted from the Uncommon Dialogue on Hydropower, River Restoration, and Public Safety, Stanford Woods Institute for the Environment, 2020.

CHARACTERISTICS, CHALLENGES, AND OPPORTUNITIES

2

2.1 NATURAL, BUILT, AND HYBRID STORAGE

Natural, built and hybrid forms of water storage offer a vast array of water storage options (figure 2.1). Large amounts of freshwater are stored naturally in ice, embedded in soils and vegetation, underground in aquifers, or on the surface in lakes and wetlands. Strategically significant water is also stored in or behind built structures such as dams, tanks, and retention ponds. Storage may also be a combination of natural and built (sometimes also called green and gray solutions) offering hybrid solutions. Managed aquifer recharge (MAR), for example, is an approach that uses built structures to accelerate the recharge of natural underground storage. While categorized for simplicity in figure 2.1, all of these storage types and systems are interconnected and part of and dependent on the overall water cycle, making all water storage hybrid to different degrees. For example, large dams and reservoirs depend on several natural elements, including the natural topography of land that forms the reservoir, and the provisioning services provided by the catchment above it.

Several types of storage and natural dynamics can work in conjunction with one another to create storage systems (box 2.1). For instance, sponge cities are an approach to urban design that is intended to absorb and store water in an urban environment. A cascade of reservoirs may be operated jointly to form a storage system. If properly managed and maintained, some natural systems—like certain wetlands, landscapes, watersheds, and floodplains—can also provide water storage. Figure 2.2 provides an overview of freshwater storage types, systems, and services.

On the global scale, natural storage accounts for the vast majority of freshwater storage. As illustrated in figure 2.3, more than 70 percent of terrestrial freshwater storage is in the Antarctic and Greenland ice sheets, and about a quarter in groundwater. The remaining forms—lakes, soil moisture, mountain glaciers, reservoirs, wetlands, etc.—collectively make up only around 1 percent of terrestrial freshwater storage.

The relative value of this storage for people depends on its location as well as its form. The Antarctic ice shelf, for example, is by far the world's biggest store of freshwater, and while it has huge environmental value for the world, given its location, it provides little to no direct storage services to people. Similarly, estimates suggest that less than 5 percent of groundwater is practically (physically and economically) available to people.

While globally insignificant compared to huge natural water stores, built storage can be highly significant at the local level, and has usually been located and designed to provide direct services to people. Built storage varies from small household rainwater harvesting tanks to large reservoirs; for example, Kariba, the world's largest reservoir, stores over 180 bm^3 of water. The various types of built storage, as well as their pros and cons, are discussed later in this chapter.

2.2 NATURAL FRESHWATER STORAGE

2.2.1 Natural Systems in Decline

All forms of natural water storage are in decline. Worldwide, anthropogenic activity is undermining natural systems and threatening nature's capacity for freshwater storage. From glaciers to wetlands to groundwater, all the ways in which nature stores water are diminishing at the global level. Glaciers are in retreat, the area covered by wetlands is being reduced, and usable groundwater is being depleted through overexploitation and contamination. Built storage is also under pressure as inefficient

FIGURE 2.1 Water Storage Types

Source: Original to this publication.

BOX 2.1 **Four Dimensions of Water Storage**

1. Natural, Built, and Hybrid

Natural water storage: All spaces in the water and soil system for (temporary) storage of surface water, rainwater, and/or groundwater. This includes snowpack, glaciers, lakes, aquifers, soil moisture, in-stream storage, wetlands, landscapes and watersheds, and floodplains.

Built water storage: Infrastructure that retains water for a determined period of time that cannot be found in nature and has been constructed artificially. This includes dams, reservoirs, in-field storage, and tanks. Built infrastructure has been instrumental to better manage seasonal water variability, and to bridge the water supply-demand gap temporally and spatially. The size of this type of storage can vary dramatically, from small water harvesting tanks to small retention dams to large-scale dams, such as the Three Gorges Dam on the Yangtze River.

Hybrid water storage: Natural and built storage can often be combined into hybrid storage systems.

2. Surface and Sub-Surface

Surface water storage: This includes water storage options, natural and built, that exist above ground, such as dams/reservoirs, tanks, and wetlands.

Sub-surface water storage: This includes water storage options, natural and built, that exist underground, such as aquifers, underground tanks, soil, and underground dams, among others. They often require a mechanism for water abstraction (pumps), and depending on the level of technology employed, can have higher construction, operation and maintenance costs than surface options, though are less susceptible to evaporation than surface water resources (van der Gun 2012). Managed aquifer recharge is a common method to replenish or maintain aquifer storage levels.

3. Small and Large

"Small water storage" refers to small-scale options to serve the water demand of small user communities. When built, they are usually located close to the water demand.

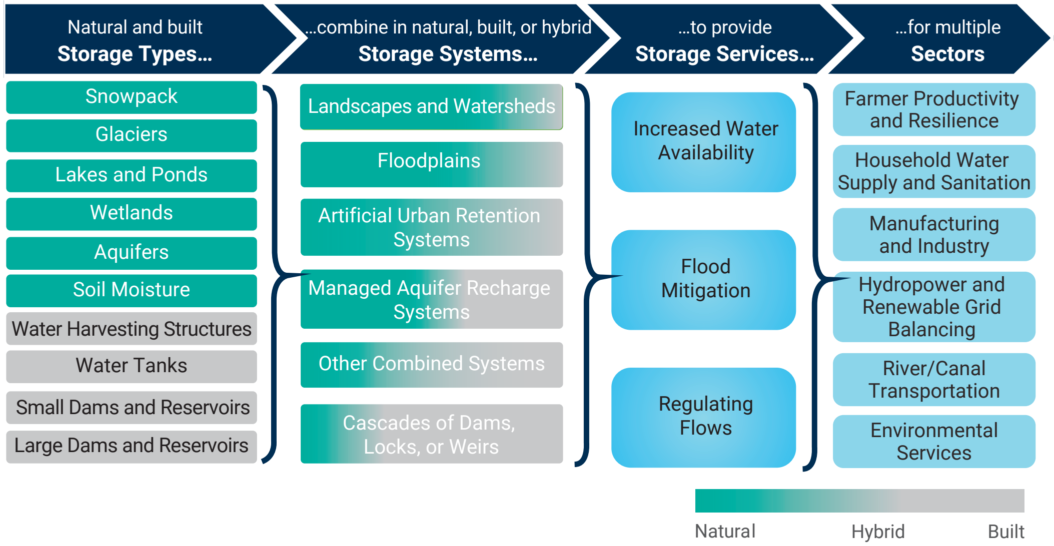
"Large water storage" refers to large-scale options that can respond to the needs of large water users, such as urban settlements, irrigation, hydropower, and industrial, or a combination of these. Because of their size, when built, they may be located far away from water users so additional infrastructure and energy may be needed for water conveyance.

4. Distributed and Centralized

Distributed water storage: Decentralized and distributed in the users' locations (e.g., storing rainwater in the soil of non-tilled fields or on terraced fields, and "harvesting" runoff water by storing it in small farm tanks), and at the scale of the micro-watershed and village (micro-dams and aquifers). Generally, management requirements are at the individual level, and downstream impacts on others or the environment depend on their cumulative scale.

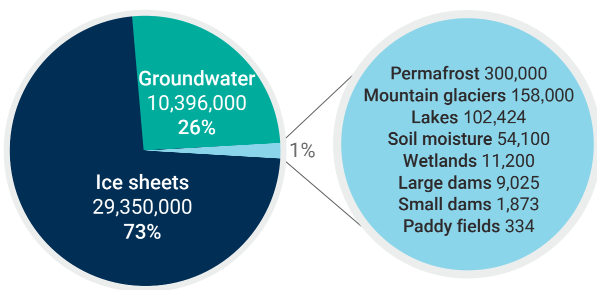
Centralized water storage: A (small, medium or large) reservoir collects surface water, and users connected to the canal or pipe system have access to water. The management requirements of the centralized options are significantly more complex compared with the distributed approach, as solutions are more sophisticated technologically, there are more actors involved, and regulations on water allocation, operation, safety, and environmental and social impact need to be in place.

FIGURE 2.2 Water Storage Types, Systems, and Services



Source: Original figure for this publication.

FIGURE 2.3 Global Freshwater Storage



Source: Adapted from McCartney et al. 2022.
Note: Amounts in bm³.

sediment management is reducing reservoir capacity. Reversing this trend is key to water security.

Glacial retreat and loss of snow cover, highly visible indicators of climate change in many regions, are dramatically decreasing and changing water storage. Widespread retreat of glaciers and snow cover loss affect human society by changing seasonal stream runoff and increasing geohazards (Huss et al. 2017). Historically, melt from glaciers has provided water during dry months, which is important for agriculture and environmental flows. Changes in these hydrological flows due to glacier retreat and snow cover loss put agricultural production, energy production, and freshwater ecosystems at risk. Geohazards are also a risk to glacier retreat and snow cover loss. The widespread expansion of glacier lakes in Nepal from 2000 to 2015 due to glacier retreat poses the threat of future glacier lake outburst floods (Rounce, Watson, and McKinney 2017), which can cause massive erosion and flooding, and threaten life and infrastructure downstream. Huss and Hock (2018) indicate that approximately half of 56 glaciated watersheds globally have already passed peak glacier runoff, putting at risk entire regions dependent on that water. With changing or diminished flows from snow cover and glaciers, groundwater reservoirs are being overexploited for irrigation and human domestic use. Overall, such variability and reduced flows provide a significant challenge to water managers to be able to sustainably manage water resources.

Wetlands—natural systems that provide flexible terrestrial water storage—are in decline because of land-use change, pollution, and sea-level rise due to climate change. Wetlands provide several vital services such as flood protection, carbon sequestration, groundwater replenishment, pollution prevention, and biodiversity services. Globally, wetlands are among the most degraded ecosystems (Ramsar Convention on Wetlands 2018). Approximately 87 percent of global wetlands have been degraded during the last 300 years, and 50 percent since the beginning of the twentieth century (Davidson 2018). It is estimated that over 50 percent of "*wetlands of international importance*" have been degraded due to pressures from agriculture, including livestock/farming, agricultural/forestry effluents, and/or land clearing (Convention on Wetlands 2021). Furthermore, wetland ecosystems are vulnerable to climate change, including sea level rise, because they normally adapt slowly to keep pace with changing environmental conditions (Erwin 2009).

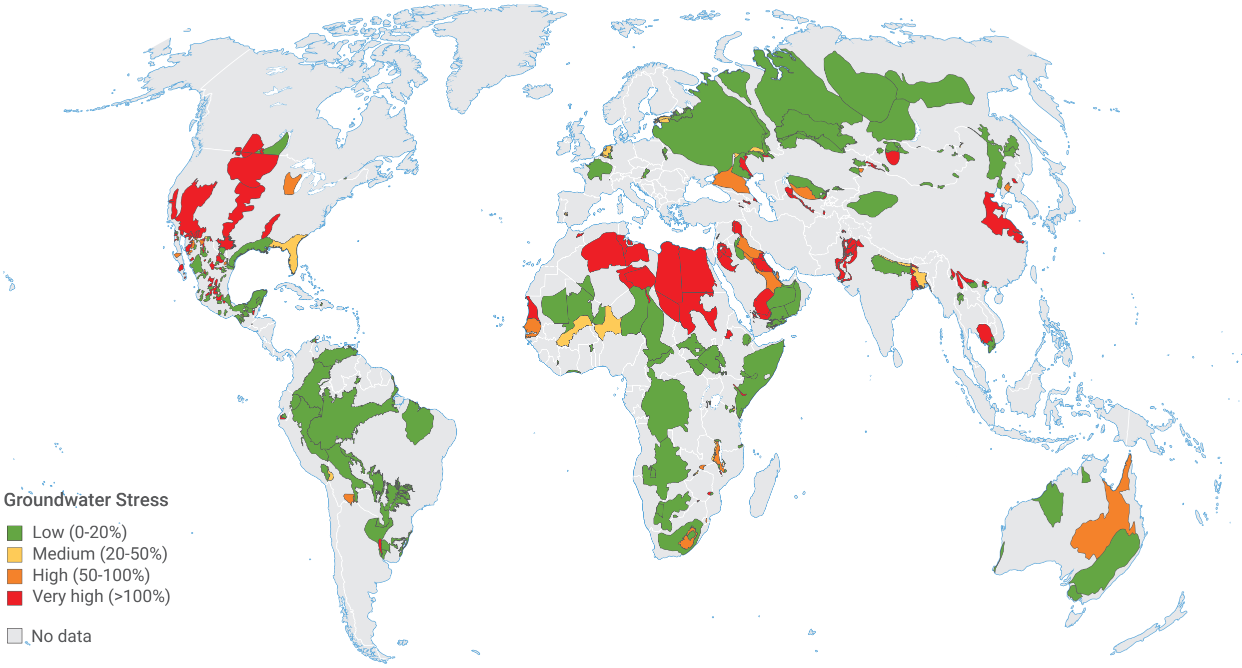
Groundwater—an unseen, vital, yet often undervalued store of water—is difficult to regulate and often poorly regulated, leading to overexploitation and massive water security sustainability challenges in some parts of the world. Even though surface water provides a larger proportion of freshwater supply that meets human water demand globally, the groundwater component is significant. The world's dependence on it has increased over time as surface supplies become less reliable and predictable, and demand increases for freshwater from growing populations. Groundwater currently provides half of the global domestic water needs (Rodell et al. 2018; UNESCO 2022), while around 40 percent of the irrigation water used to grow the world's food is supplied from underground sources. The exchange between surface water and groundwater means there is an overlap of resources (where the same volume of water flows between surface and groundwater). This overlap is often not recognized, leading to "double counting," an overestimation of available water and the depletion of groundwater resources that have increased during the last decades. This increase is likely to continue (Rodell et al. 2018). The magnitude of global groundwater depletion has been estimated through Gravity Recovery and Climate Experiment (GRACE) satellite measurements (Famiglietti 2014; Rodell et al. 2018). Because of its wide distribution and accessibility, groundwater is difficult to manage where regulation is weak, and usage is not measured. Ignorance about the overlap between groundwater and surface waters, and of the long-term impacts of allowing it to become contaminated, add to the physical pressures on groundwater availability. The difficulty of regulating its use is a challenge that has huge implications for future water security. The problem is often exacerbated by a lack of information and data on the status of aquifers, resulting in a large element of uncertainty in determining when unsustainable levels of abstraction have been reached.

Groundwater extraction rates differ significantly across the world, with some areas, including parts of Sub-Saharan Africa, still underexploiting groundwater relative to its potential sustainable yields. From 1960 to 2010, groundwater extraction worldwide more than tripled, going from 312 km^3 in 1960 to 968 km^3 in 2010 (UNESCO 2012). More than half of the world's 37 largest aquifers are being depleted, according to NASA data (Richey et al. 2015). Much of this increased level of extraction has come from arid and semiarid parts of the world, with irrigation as the largest driver of groundwater depletion worldwide (UNESCO 2022). Groundwater overuse also occurs because of high population density, heavy reliance on groundwater, little or highly variable rainfall, and low rates of natural recharge (Fienen and Muhammad 2016). While global trends have been trending in one direction, local circumstances differ widely around the world, with some areas overexploiting their groundwater resources and others underexploiting them (map 2.1).

Contamination of groundwater, either from pollution or from mismanagement, severely diminishes the world's ability to harness water stored in aquifers. Overexploitation of groundwater is not the only threat to this type of natural water storage. Contamination of groundwater limits the amount of water that is available to both humans and nature. While natural contamination exists (e.g., from arsenic, fluoride, and salinity) that may be exacerbated by overextraction, contamination introduced by humans is increasing and is usually preventable. Agricultural contaminants (such as pesticides and fertilizers), industrial and domestic waste disposal, wastewater treatment plant discharges, seepage from petrol filling stations and sanitation systems, and industrial discharges all threaten the quality of groundwater. Given the importance of groundwater, especially with the increase of water scarcity, maintaining and increasing water security will invariably depend on sustainably managing groundwater and activities that affect its quality.

Groundwater misuse and mismanagement can have compounding effects and can destroy the possibility of using aquifers for storage in the future—further depleting our storage capacity. Groundwater withdrawal and depletion can cause several issues, including exacerbation of hydrological droughts (e.g., reduced summer flow due to decreasing groundwater), cause declining water tables, springs to dry up, seawater intrusion, shrinkage of wetlands, water pollution, and negatively impact groundwater-dependent ecosystems. All these impacts translate into a reduction of water availability—both in quantity and quality—and can in turn further increase groundwater depletion as other water sources become scarcer. Further,

MAP 2.1 Groundwater Stress



Source: Based on IGRAC 2022.
Note: Groundwater stress is defined as the ratio percentage of mean annual groundwater withdrawals over the mean annual groundwater recharge (IGRAC 2022). This map is based on a global dataset. Countries may have more detailed maps depicting groundwater stress/depletion nationally that is not reflected here.

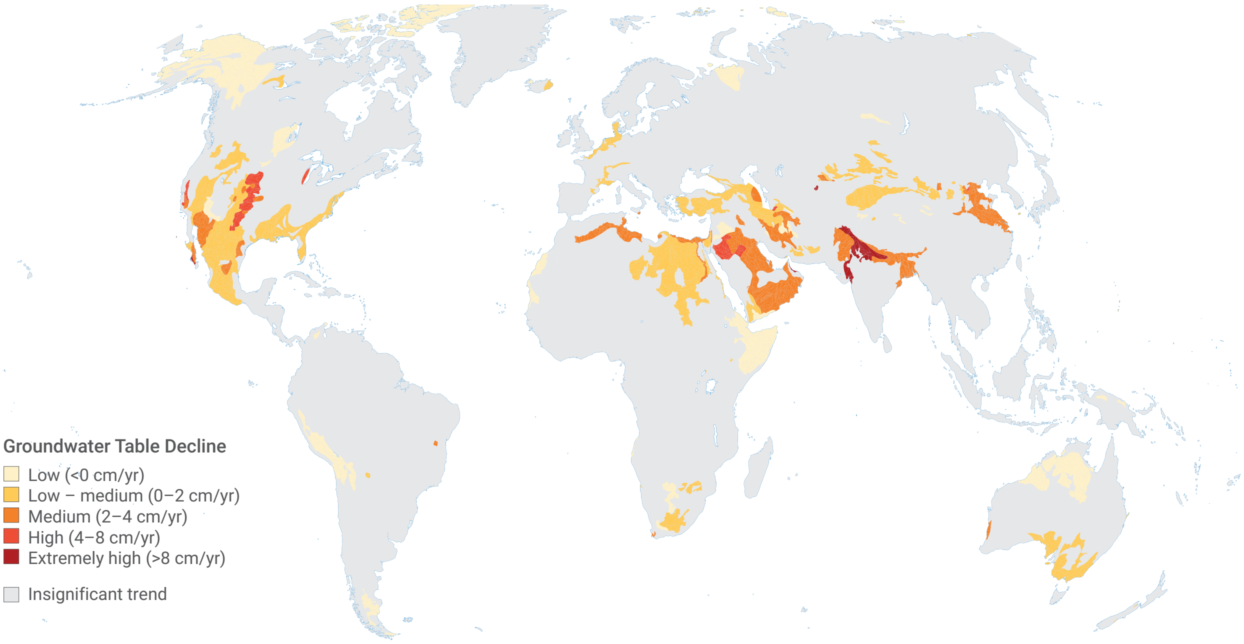
if aquifer overdraft and land subsidence are inelastic in nature, this can prevent using the aquifer for any future storage, even from natural replenishment. The areas experiencing the highest levels of decline are shown in map 2.2. Although essential to regional irrigated agricultural economies, continuing groundwater overexploitation in such regions is unsustainable. Aquifer contamination may not affect its storage capacity, but the economic viability of aquifer storage reduces if the groundwater stored in such an environment requires extensive treatment to be usable.

Soil moisture—a critical water store for agricultural production and ecosystem health—is expected to continue to decline as temperatures rise. The rising of temperature due to climate change is expected to increase land surface evapotranspiration, in turn reducing soil moisture, which can lead to agricultural and ecological drought, reducing agricultural production and ecosystem services, respectively. At the same time, climate change also may affect soil characteristics, which in turn may affect soil moisture storage properties. Most existing analyses of future surface soil moisture with climate change show widespread decreases in soil wetness, with no regions displaying significant increases (Berg and Sheffield 2018), supporting projections of increased land drying, although there are large uncertainties. Models indicate a slight decrease in mean soil moisture levels, with the more significant changes in soil moisture projected in regions of lower precipitation. This corresponds to an increase in drought conditions (area, duration, and frequency) (Berg and Sheffield 2018). In terms of soil moisture, continuing declines can increase the need for irrigation in agriculture or lead to smaller yields and even desertification, with potentially significant impacts on food production (EEA 2019).

2.2.2 Nature's Ability to Meet Demand

Large amounts of natural storage are inaccessible to humans. At the global scale, the largest stores of freshwater—the Antarctic and Greenland ice sheets—are largely inaccessible to large-scale human use. Similarly, some of the largest aquifers are under major deserts or are at depths that make their use uneconomical or inadvisable due to the permanent geological deformation that would result.

MAP 2.2 Groundwater Table Decline



Source: Based on WRI 2022.
Note: Groundwater table decline measures the average decline of the groundwater table as the average change for the period of study (1990–2014). The result is expressed in centimeters per year. Higher values indicate higher levels of unsustainable groundwater withdrawals (WRI 2022). This map is based on a global dataset. Countries may have more detailed maps depicting groundwater stress/depletion nationally that is not reflected here.

Natural storage may not meet water demand. At the more local scale, while early human settlements were heavily influenced by the local availability of water, larger and more concentrated populations have sometimes meant that use of water has outstripped supply: in some places, built water storage is needed in addition to natural, and water is transferred from other basins to meet demands. In addition, human development patterns are influenced by many factors beyond water, including the availability of land, location of minerals, strategic locations for trade, and political decisions, among others. This means that cities and other centers of demand may be located far away from adequate water supplies, or natural storage systems. The Gauteng region in South Africa, for example, has long struggled with ensuring adequate water security as demand for water outstripped local availability to serve its growing economy and population. Early settlements used local rivers and groundwater, but the discovery of gold in the 1880s led to demand rapidly outstripping the volumes of water naturally available, and a series of investments in built water storage and inter-basins transfers followed over the next century (Dippenaar 2015)—some with large ecological impacts.

2.2.3 Harnessing Natural Storage

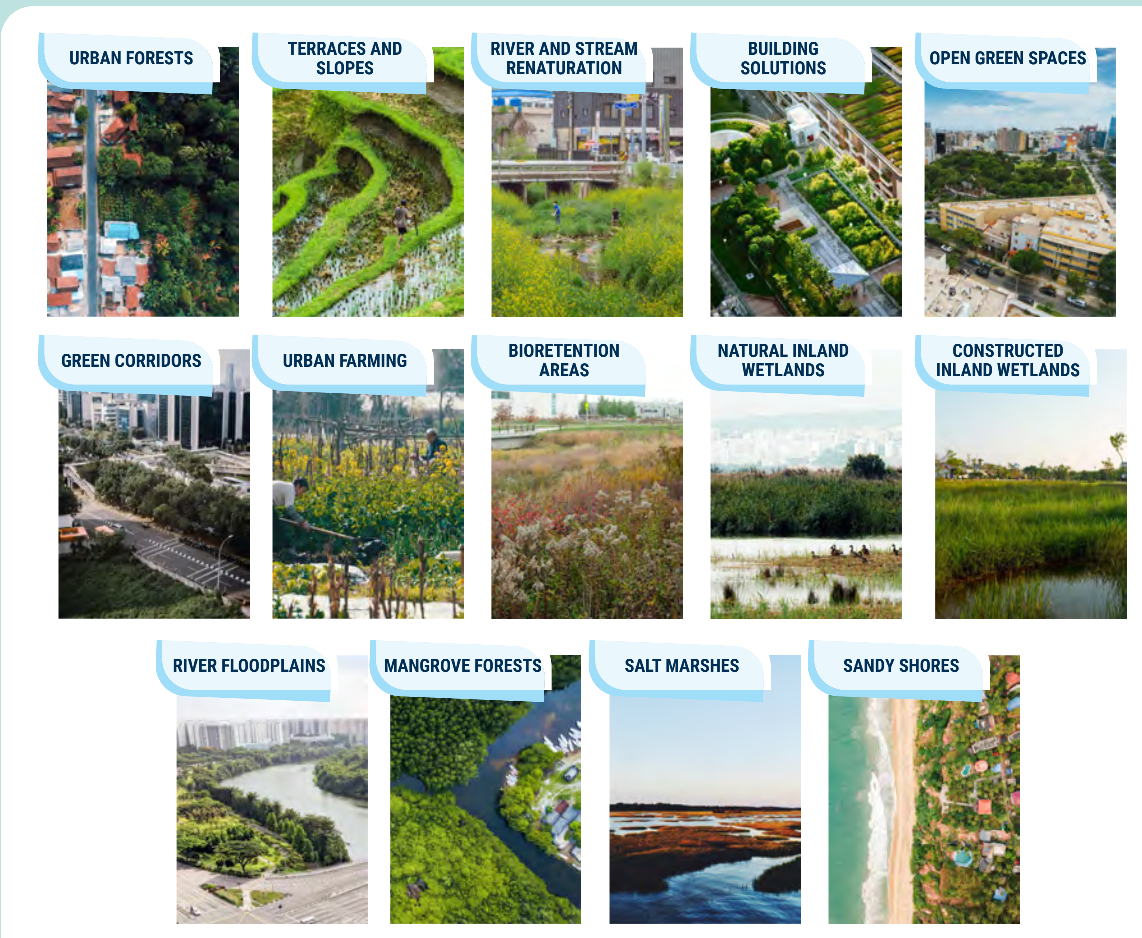
Natural storage mitigates floods, increases water availability, and regulates downstream water levels. Many forms of natural storage can provide effective flood mitigation services by absorbing and slowing the flow of water. Indeed, many downstream communities have discovered how effective natural storage was in mitigating floods in retrospect as upstream land-use changes resulted in a very different precipitation runoff response and worsening floods from the same amount of precipitation (see box 2.2 for examples of urban flood resilience). Natural storage can also enhance dry season water availability through the slow release of water, such as mountain glaciers and snowpacks in parts of Asia, Europe, and South America have been shown to significantly improve downstream flows during the dry season. Depending on their absorptive capacity, large wetlands can also act as sponges, absorbing wet season flows and releasing the water over the dry season.

BOX 2.2 Catalogue of Nature-Based Solutions for Urban Flood Resilience

The World Bank *Catalogue of Nature-Based Solutions for Urban Resilience* (World Bank 2021a) is a flagship report that was jointly launched by the Global Program on Nature-Based Solutions (NBS) for Climate Resilience and the City Resilience Program, both housed in the Global Facility for Disaster Reduction and Recovery. The catalogue lays out the 14 main typologies of nature-based interventions for climate resilience in cities found in figure B2.2.1, and provides illustrative designs, examples, information on costs, benefits, implementation considerations, and generic principles for integrating NBS into urban environments. Detailed examples of landscape architecture designs at various scales have been developed to help visualize how the solutions fit in the urban context.

The catalogue was created as a resource for those aiming to shape urban resilience with nature by enabling an initial identification of potential investments in NBS. Many urban resilience building professionals who make planning, financing, and technical decisions have limited knowledge of how and when to build with nature. The catalogue supports policy makers, project developers, development professionals, urban planners, and engineers with the identification of potential NBS investments and provides the tools to start a policy dialogue on NBS in cities.

FIGURE B2.2.1 Examples of Natural Storage



Source: World Bank 2021a.

(box continues next page)

BOX 2.2 Catalogue of Nature-Based Solutions for Urban Flood Resilience (cont.)

Project: Chulalongkorn Centenary Park, 2012–17

Location: Bangkok, Thailand

Description: The Chulalongkorn Centenary Park is the first crucial piece of green infrastructure in Bangkok. Designed to mitigate detrimental ecological issues, it has added a much-needed outdoor public space to the gray city in 2017. The green roof is the largest in Thailand; the filtration system treats water from neighboring areas. The park water treatment system is built around constructed wetlands with detention lawns and retention ponds. The constructed wetlands follow the slope of an inclined plane and step down through a series of weirs and ponds. Passing through a weir, water cascades, flows through a plant-filled pond below, passes through another weir, and flows through another pond. Water is cleaned every time it passes through plants until it reaches the retention pond, where children and adults can safely play and enjoy the water. Chulalongkorn Centenary Park has become a showpiece for ecological and social impacts of landscape architecture in dense urban areas. The site area spans 48,000 m² and is 1.3 kilometers in length, and it sits in the campus area of Chulalongkorn University.

Sources: LandProcess, Kotchakorn Voraakhom (http://www.landprocess.co.th/); Holmes 2019.

Project: Araucárias Square: Rain Garden and Pocket Forest, 2017–18

Location: São Paulo, Brazil

Description: This is one of the first rain gardens implemented in a Brazilian city with the active involvement of residents. The garden collects runoff across a surface of 900 m² that would otherwise go directly into the drainage system, and which used to flood lower areas of the city. After the garden's implementation, the vegetation thrived, and runoff was reduced. Residents and leaders of the grassroots movements actively participated to transform this remnant derelict piece of land. In an effort to plant pocket forests in small plots of land, social media was employed to invite and challenge volunteers. This social experience, with people of all ages coming from various districts to actively contribute to nature's reconstruction in the park, has also led to private funding contributions to maintain and protect the new pocket park.

Source: CARDIM Arquitetura Paisagística. https://oppla.eu/casestudy/20079; http://www.cardimpaisagismo.com.br/portfolio/largo-dasaraucarias/

Project: St. Kjeld's neighborhood: Tåsinge Plads, 2013–15

Location: Copenhagen, Denmark

Description: The bioretention project is part of The Climate Neighborhood project, in the St. Kjeld's neighborhood, launched as a neighborhood renewal program. The bioretention area was sloped to collect rainwater at the bottom where it seeps into the ground, instead of being directed to the drains. Water from the streets collects in waterbeds, which are filled with mold that filters the water. This climate adaption creates capacity in the drains to prevent flooding. The entire St. Kjeld's neighborhood is a showcase for ground-breaking climate adaptation solutions.

Source: City of Copenhagen, HOFOR, GHB Landskabsarkitekter. https://urban-waters.org/sites/default/files/uploads/docs/tasinge_Plads.pdf

Project: Usaquén Urban Wetland, Completed in 2016

Location: Bogotá, Colombia

Description: The 8,500 m² landscape project, completed in 2016, aims to transform and revitalize an emblematic public space in northeastern Bogotá. Its design concept is based on the wetlands of the Bogotá Savannah, a neighboring rocky area, and the typical plant species. The project re-creates the geometry of the half-aquatic, half-terrestrial ecosystem, its colors, and textures. A rainwater garden in the main square uses recycled water and creates a native urban wetland that blends with its surroundings and the Andean hill backdrop, and preserves the native vegetation in its natural habitat. Underpinned by a clear, rationalized structure and construction style within its spatial composition, the urban design's aspects are seemingly wild, natural, and freeform.

Source: Obraestudio. https://www.archdaily.com/912462/usaquen-urban-wetland-cesb-obraestudio

Natural storage cannot always be translated into controllable bulk water supply. With the exception of groundwater, most natural storage cannot readily be tapped for bulk water supply of the sort needed for household water supply, industrial use, or irrigation. It also cannot be turned on or off in the short term. From a societal perspective, the value of natural storage depends on the services that people require. Soil moisture, for example, is directly useful for farmers but only indirectly beneficial to cities or hydropower operators.

Natural storage may need more time than built storage to retain flows. For instance, the dynamics of natural groundwater storage may mean that more time is needed to capture water—and only some of the flow is collected. Because water enters aquifers through infiltration (or sometimes through artificial injection wells), time may be needed to transfer the water into the aquifer. As such, natural storage such as aquifers may not be as effective in capturing the entirety of large volumes of flow over a short period of time, such as seasonal snow melt. However, they can be used to capture flows over a longer period of time and may be able to simultaneously improve water quality through the infiltration process.

2.3 BUILT SOLUTIONS AND CHALLENGES

Built storage infrastructure provides societies with the flexibility to locate storage where they need it and improves controllability for provision of storage services. Water stored in human-built systems,[1] from household tanks to large dams, represents less than 1 percent of accessible freshwater storage on earth. However, built storage is developed in response to specific needs, and is therefore generally in locations and forms that provide direct services to users. Built water storage has been instrumental in increasing and securing water availability during droughts, in supplementing water for irrigation when rain is insufficient, for hydropower, and for the regulation and control of floods.

Besides large reservoirs and dams, other types of built storage include small reservoirs and dams and a variety of forms of ponds and tanks.[2] Small water retention structures, such as small dams, ponds, and tanks, can be found around the world, where they are known under multiple names: johads, açudes, small reservoirs, and micro-dams, among others. Small water retention structures can serve the small, immediate water needs of different water users, and can be built closer to where the water is needed. Large built structures can ensure long-term availability, be designed and operated as multipurpose facilities, and support nearby smaller dams (Blanc and Strobl 2014). Large dams provide substantially greater storage capacity, operate at a lower per unit cost (though with higher total investment and operation costs), and lose less water owing to evapotranspiration when compared to small dams (Blanc and Strobl 2014). They can also be operated as a form of battery when configured as a pumped storage hydropower scheme by pumping water to a higher-level storage when energy costs are low and releasing the water at a time when hydropower generation is needed. The relative weight of the advantages and disadvantages of large versus small built solutions depends upon various factors involved, such as climatic and geophysical conditions, water demand to be supplied, longevity, and costs (box 2.3).

2.3.1 Dams and Reservoirs

Dams, and the reservoirs behind them, are the most significant form of built storage. According to the Global Reservoir and Dam Database (GRanD) database, which contains data for 7,320 dams greater than 15 meters in height or with a reservoir of more than 0.1 km^3, there is an estimated 6,863.5 km^3 of storage capacity from large manmade reservoirs. Smaller reservoirs are estimated to represent an additional 1,873 km^3 of storage (Lehner et al. 2011). Map 2.3 shows the spatial distribution of dams worldwide.

The location of built storage is, to some extent, based on human choices, but the location of dams and reservoirs is highly dependent on the opportunities provided by local topography, hydrology, geology, accessibility, and proximity to demand centers. From a purely hydrological perspective, good sites for dams require a place where nature can trap water (such as a valley) and the required flow of water through that space, and where the downstream impacts of changing river flows can be adequately mitigated. In practice, good dam sites are naturally occurring and scarce, and in many parts of the world have already been utilized. The expansion of dam-based storage is therefore not simply a matter of what can be built but also

BOX 2.3 Dam and Reservoir Inventory Using Remote Sensing and Artificial Intelligence

Problem

Dams and reservoirs account for the majority of built storage capacity around the world and are used as an important water management measure to augment supplies and protect from floods, as well as specific economic purposes such as power generation. Understanding the existing portfolio of dams is an essential step in characterizing the water management space. Preparing an inventory of dams is essential from an integrated storage management perspective as it provides a basis for siting new storage, connecting reservoirs to other hydrological features, conjunctive use planning, and informing flood risk management. Establishing a dam inventory is also the first step in dam safety assurance so that an appropriate dam safety management system can be put in place.

Despite their economic importance, associated risks, and numbers, it can be very difficult to complete an inventory of all existing dams. Dams, large and small, can be constructed and operated by a range of government authorities at the national or local level, or by private owners for irrigation, hydropower, mining, or other purposes, sometimes without centralized government knowledge or oversight. In the absence of a complete inventory, it is difficult to assess the total storage volume and impact of available storage on the larger hydrological system and plan for flood risk prediction and protection.

Approach

Improvements in remote sensing technologies and pattern recognition and machine learning algorithms are creating new opportunities for quick and cost-effective identification and mapping of dams and reservoirs. Open-source semi-automated algorithms can be developed to locate and identify basic reservoir properties including geometry, size, and type of dam, as well as delineate the dam bodies attached to the reservoirs.

The process includes preparation of training data, including preparation of preliminary analytical algorithm, calibration of the algorithm using training data, and full implementation in the geography of interest. Possible methods to distinguish artificial reservoirs from natural water bodies include (a) use of surface reflectance characteristics of the reservoirs; (b) pattern recognition (geometric patterns are unique to artificial reservoirs); (c) seasonal fluctuation of reservoir areas caused by dam operation; and (d) relative altitudinal gap between the reservoir surface and downstream area. Possible methods to delineate the dam bodies attached to the reservoirs include (a) use of surface reflectance characteristics of dam bodies; and (b) pattern recognition of high-resolution visual imagery.

Incremental development across national portfolios can help deliver a geo-referenced global inventory of dams, which can in turn be used in tandem with online global forecasting systems to improve dam safety and safety of life and property downstream. In Zambia, using remote sensing techniques, 1,022 reservoirs were identified in the Southern Province alone in 2011 (Wishart et al. 2020). Based on physical verification efforts being carried out by the government, the official estimate of dams in the country currently stands at 1,700 dams, situated mostly in the drought-prone, semi-arid areas of the Eastern, Lusaka, Central, and Southern provinces.

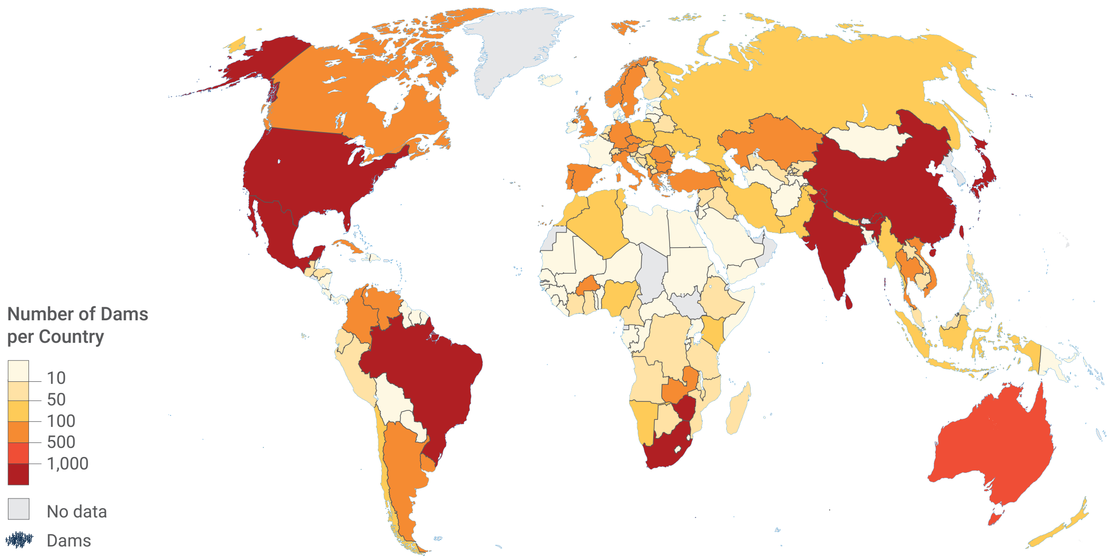
Good Practices

Under maximum assurance, preparation of an inventory requires that all dams be registered and classified based on size or a combination of size and hazard, ideally shared publicly in a well-maintained database. Classification can be used for proportioning dam safety mandates such that higher requirements on surveillance and design standards are applied to higher-hazard dams, and lower requirements to lower-hazard dams, thereby allowing optimal allocation of available financial and human resources.

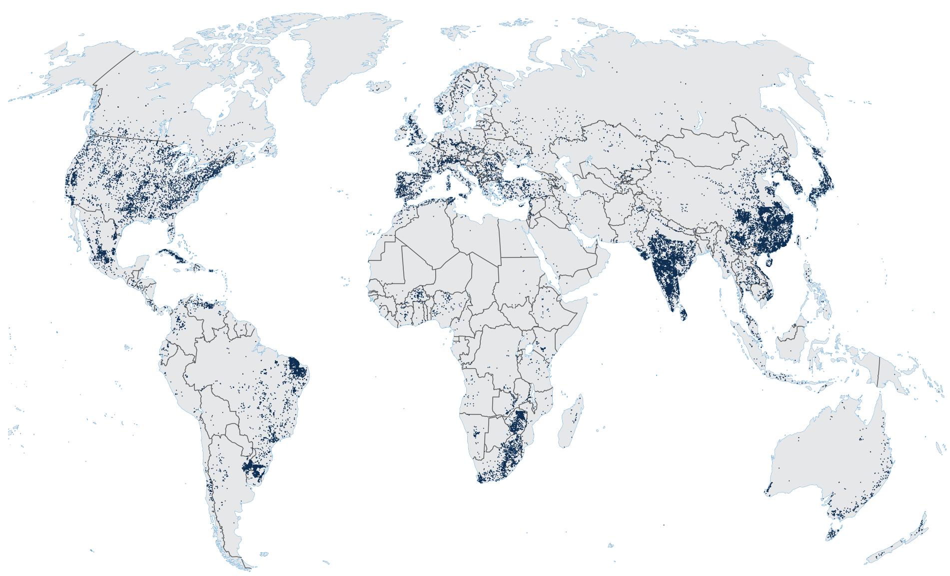
At minimum, local authorities should maintain a register of dams in their jurisdictions, with assigned hazard ratings. This can help monitor the density of hazardous dams and continually update assessments of potential risks to downstream areas as they develop.

MAP 2.3 Distribution of Dams

a. Number of dams per country



b. Location of dams



Source: Based on Mulligan, van Soesbergen, and Saenz 2020.

the range of opportunities that local hydrological systems and other factors provide.

2.3.2 Sedimentation of Reservoirs

While the extent depends on the specific dam and river conditions, it is broadly true that rivers transport sediment and dams trap sediment. Rivers transport both water and sediment as they flow from source to sea. When undisturbed by human activity, the quantity of sediments transported by a river is determined by hydrological processes, topography, and natural soil erosivity in its watershed. Floods and tectonic forces can change the equilibrium between river and landscape temporarily. This equilibrium sustains the geomorphic and aquatic health of river systems. When reservoirs are built, a barrier is created, which can trap large amounts of sediments carried by the river.

In the absence of sediment management, the capture of sediments by reservoirs can create many problems for dams and reservoirs. For sand dams, the trapping of sediment is a design feature and core to the way they operate to store water in ephemeral rivers. For traditional dams and reservoirs, sedimentation is a threat to the available storage volume. As available storage volumes decline, so does the capacity to provide reliable water supply and generate power. Reduction in storage volumes also reduces the capacity to hold flood waters, increasing flood risk and dam safety risks. Sediment can damage electromechanical equipment, hydraulic machinery, and civil structures that are important for the safe operation of dams; it also speeds up the wear and tear on parts and equipment such as turbine runners, necessitating their replacement before the expected end of their operational life.

Sedimentation of current dams is reducing built storage volumes around the world. Loss of existing water storage due to reservoir sedimentation is estimated to be between 0.8 and 1 percent per year, contributing to a decrease in per capita water storage to 1960s levels (Annandale, Morris, and Karki 2016). Once lost, it is very expensive to replace storage volume—either through new storage investments or by recovering storage by removing sediment. In 2003, it was estimated that $13 billion would be required to replace storage volumes lost annually (Palmieri et al. 2003). Globally, sedimentation causes hydropower production losses of 1 percent annually (HydroSedi.Net 2022), due to loss of storage and damage to equipment.

Trapping sediment in dams also increases erosion downstream and threatens aquatic ecosystems. The water released downstream of a dam, without effective sediment management, is starved of sediment. As these flows have greater capacity for transporting sediment, this leads to erosion of the riverbed and riverbanks downstream. Reservoir sedimentation can also contribute to coastal erosion by starving delta areas of important sediment deposits, which, when combined with groundwater over-abstraction, can contribute to subsidence and increased salinity (Basson 2005). Reductions in sediment transport downstream of dams also means reduction in nutrient transport, which can affect total availability of nutrients and lead to a decline in aquatic ecosystems and fish stocks.

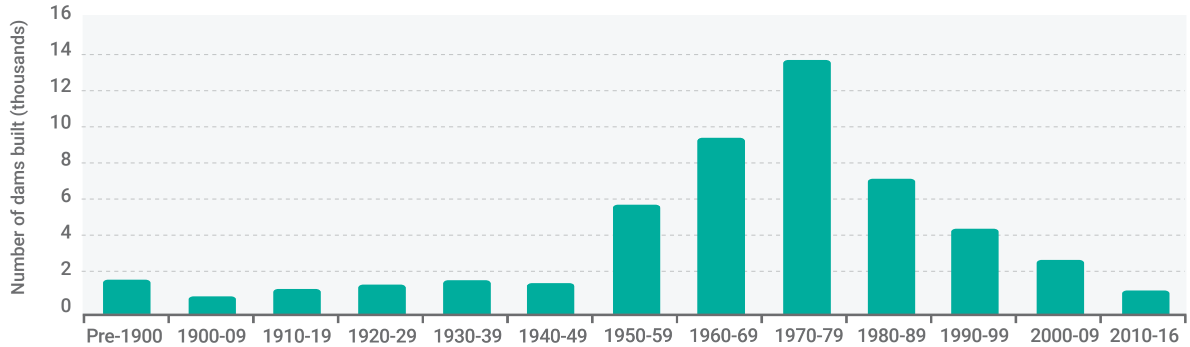
There is an acute need for better planning and operational approaches to improve sustainable sediment management in existing and new reservoirs. Sediment management approaches range from those that avoid trapping sediment in the first place, such as reducing watershed erosion and routing sediment through or around the reservoir, to approaches such as flushing and dredging, aimed at the removal of sediment and recovery of usable storage volume, to creating "dead storage," and dedicated space in a reservoir for sediment (although this is a limited solution that must include wider sediment management). Sustainable sediment management should be an early planning consideration and reflected into the design of storage facilities. Awareness of the importance of sustainable sediment management is increasing with time and as more data and tools emerge for water managers and planners; still, there are a large number of facilities designed without proper sediment management strategies, contributing to a gradual loss of built storage capacity. Overall, a shift in approach is needed for sediment management. Instead of viewing reservoirs as limited resources that are to be abandoned due to sedimentation over time, reservoir and storage assets should be managed and viewed as renewable resources.

2.3.3 Built Storage in Decline

New dam construction continues but at a slower pace. For a variety of reasons, the number of new large dams being constructed is much lower compared to the 1950s through 1970s (figure 2.4). Large dams have been the subject of criticism by some civil society organizations (CSOs) and local communities due to the negative impacts of some projects on people and nature, which has led to increased awareness globally of the social and environmental impacts of dams. In addition, many of the dam sites with better natural conditions have been already developed in many countries, particularly high-income countries—especially as many older sector plans ranked investments by least cost. Meanwhile, the high capital costs of large dam projects constrain their development, particularly in low- and middle-income countries where there is generally less fiscal space and technical capacity, and where risk—and in some cases, creditworthiness—can deter investors.

The stock of dams is aging, standards are changing, and some dams are becoming obsolete. There are a number

FIGURE 2.4 Development of Dams over Time



Source: Wishart et al., 2020 based on ICOLD World Register of Dams.

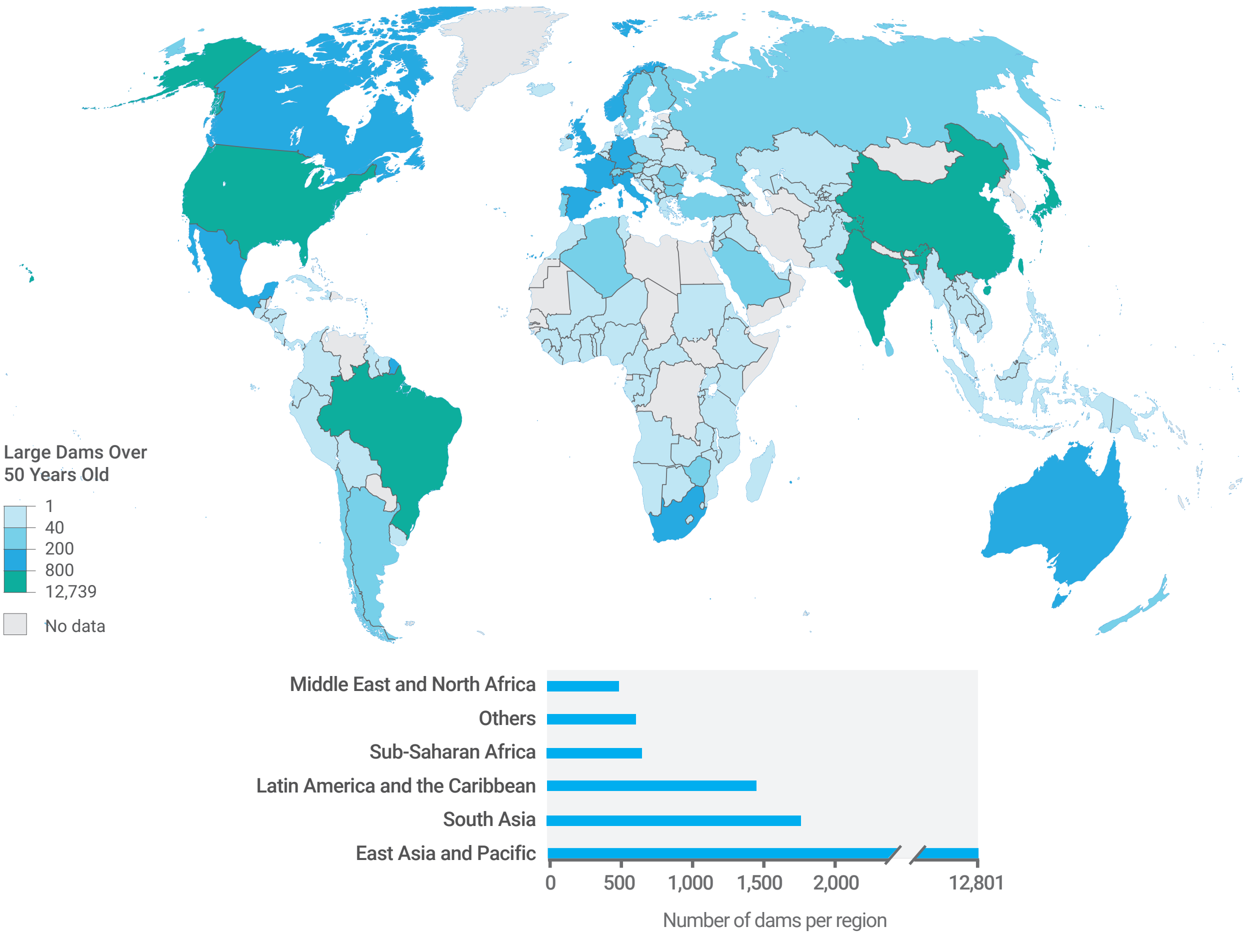
of dams operating around the world today that are well over a century old. Given the global dam-building boom from the 1950s to 1970s, many others are between 50 and 100 years old (map 2.4). Age alone is not necessarily a problem for a dam if it was well constructed, appropriately maintained, and periodically rehabilitated when needed. However, for many dams, both the physical and regulatory environment has changed since they were designed and constructed. With climate change increasing variability and the occurrence of extreme events, some dams no longer have sufficient flood-handling capacity and need to be upgraded. Also, as engineering standards and environmental regulations evolve to reflect new understanding and changing attitudes, some dams need major upgrades to remain in or regain compliance. In some cases, these rising maintenance and rehabilitation costs for older dams may tip the scale for considering their decommissioning.

Decades of deferred maintenance pose challenges that range from sub-optimal performance to risks of catastrophic failure. Maintenance of existing water storage infrastructure is often a low priority, and insufficiently funding maintenance generally results in a lower level of service provision. This is due to a range of factors, including competition for funding with other urgent national or regional priorities, lack of expertise, inadequate consideration of operation and maintenance (O&M) costs at an early stage, and a possible bias by water managers toward realizing new investments to overcome a services deficit. More severe impacts of poor maintenance and/or operation can lead to increased risk of flooding and even dam failure. The World Bank, for example, has seen an increase over the years in dam rehabilitation and major maintenance projects. Between fiscal years 2002 and 2021, the Bank approved more than 140 projects related to dam rehabilitation or upgrading, including national-scale or similarly large rehabilitation projects. While approximately 40 percent of World Bank-financed projects involving dams included dam rehabilitation, more than 70 percent of the actual dams supported were the subject of rehabilitation. A significant proportion of this work, particularly in South and Southeast Asia, is addressing safety improvements and deteriorated conditions from deferred maintenance across a country's portfolio of dams.

2.3.4 Environmental and Social Trade-Offs

If not well planned, dams can create significant environmental, social, and economic impacts that need to be carefully considered, mitigated, and compensated for, where appropriate. Some negative impacts of dams are well documented. Construction of a dam may involve land acquisition or involuntary resettlement; this physical and economic displacement of communities can weaken social networks, diminish cultural identity, disrupt livelihoods, and even lead to impoverishment. Physical cultural heritage can be lost to reservoir impoundment or damaged during construction. Dams also reduce the connectivity of rivers, change their flow regimes, and degrade their water quality, which can affect aquatic and other species that inhabit freshwater ecosystems. This is of particular concern for migratory fish species that traverse the lengths of rivers for feeding and breeding. Dams can also lead to waterborne diseases, biodiversity loss, and colonization of exotic species.

MAP 2.4 Large Dams Over 50 Years Old



Source: Based on ICOLD World Register of Dams.
Note: Number of large dams over 50 years old by country and region.

The extent of these impacts differs significantly by the nature, location, and operating regime of the dam. Large dams in relatively flat landscapes will inundate much larger areas than dams constructed in deep valleys. Hydropower schemes operating as baseload are generally better able to mimic natural downstream flows than those operating as peaking facilities. Several small dams in a basin could potentially have greater cumulative impacts than a single large dam, while a new dam on a free-flowing river stretch could have significantly greater impacts than a new dam in a heavily regulated branch of a river (Ledec and Quintero 2003). Hydrological investments can also have uneven distributions of costs and benefits for upstream groups compared to groups downstream, as well as between those who do and do not directly benefit from the regulation of the water. This is true in shared watercourses as well, where the construction of dam infrastructure creates distributional impacts across international boundaries. While important to consider, the distributional consequences of dams are difficult to measure due to the long time horizon over which the costs and benefits materialize. Selection bias is also a challenge as hydrological investments are placed in favorable geographies, and the distribution of costs and benefits may be influenced by dialogue between project planners and local communities, which have their own complex political economies (Dillon and Fishman 2019).

Informed planning is vitally important to avoiding and reducing the negative impacts of storage projects, including dams. Not every dam that is technically feasible is economically, socially, and environmentally feasible. By constructing a barrier across a river, dams, by definition, alter the landscape in which they are placed and create trade-offs against other development goals. The impacts of a dam and the potential for their mitigation are, therefore, largely determined by the decision of where to site a dam. By avoiding sites that are of high conservation value, while involving project-affected communities as real stakeholders from early on, storage planners and developers can reduce environmental and social risks, improve the acceptability of storage investments, and avoid high costs of mitigation and compensation. Building these considerations and constraints early into storage planning produces a more realistic picture of storage options that reflect the full social costs and benefits of potential investments (Meng, Devernay, and Lyon 2014; Opperman et al. 2015).

Several international initiatives have outlined ways to approach dams so as to maximize benefits and minimize negative impacts. The World Commission on Dams, launched in 1997, ushered in an era of multi-stakeholder, evidence-based approaches to improving the sustainability of dams (Bird and Wallace 2001). While often critiqued as difficult to implement, the Commission's report contains principles and guidelines based on a "rights and risks" framework that has inspired many other actors to develop implementable tools, guidelines, and system planning approaches to operationalize these principles (ADB, MRC, and WWF 2013; IHA 2021; Opperman et al. 2015; Skinner and Haas 2014), including the World Bank's own Environmental and Social Framework (World Bank 2019c), the Performance Standards of the International Finance Corporation (IFC 2012), and the Multilateral Investment Guarantee Agency (MIGA 2013). The World Bank has also developed a number of resources on dam safety (box 2.4). This report recognizes that immense body of work, and while chapter 5 summarizes good practices at different stages of a storage project's life cycle, the main focus of the report is on the early planning phase and assessment of storage options through a more integrated lens.

2.3.5 Hydrological Risks

Dams are long-lived structures and should be designed to withstand hydrological extremes; as a result, they are

BOX 2.4 Dam Safety

Dam safety is defined in various ways, often depending on the country context, but it can be considered *"the art and science of ensuring the integrity and viability of dams such that they do not present unacceptable risks to the public, property, and the environment"* (FEMA 2019). The main pillars of a dam safety program are (a) adequate engineering design and construction, (b) regular surveillance (monitoring and inspections), (c) adequate operation and maintenance (O&M), and (d) plans for dealing with emergencies.

The basis for an effective dam safety management system is a fit-for-purpose regulatory framework, the foundation of which is an enabling legislative framework that establishes minimum standards as well as duties, roles, and responsibilities for assuring the safe development and operation of dams. Also essential is a well-defined institutional framework that is clear on the responsibilities for ownership and operation of dams as well as oversight of dam safety assurance. The technical content of the regulatory regime will contain mandates for how to define which dams are regulated, how such mandates are proportioned according to size or hazard, standards and criteria for dam design, requirements for surveillance and O&M, technical guidelines, education, training, and, lastly, compliance enforcement.

Regulatory frameworks for dam safety, while largely defined by the type of legal system and the constitutional basis for lawmaking and administration, should be informed by the size of a country's portfolio of dams, their geometric dimensions, their hazard potential and vulnerability, and the degree to which there is public or private ownership. These factors will determine where along a continuum from minimum to maximum safety assurance the most appropriate framework for that jurisdiction lies, considering that moving along the continuum from minimum to maximum assurance has cost and capacity implications.

Sources: Wishart et al. 2020; World Bank 2020a, 2021b.

costly endeavors. Before even breaking ground on a new dam, significant studies should be undertaken, including geological investigations, feasibility studies, environmental and social assessments, and detailed engineering designs. The costs of construction vary greatly, and not only according to size but also according to the geological conditions, ease of access, method of construction, costs of environmental and social risk management, costs of financing, and many other factors.

Cost and schedule estimation for built infrastructure is not an exact science. Uncertainty around the development cost gradually narrows the more study has been done and the closer the project is to a final design, but it is never eliminated. Cost and schedule overruns are a persistent challenge in large infrastructure, and large dams are no exception. Data from large hydropower projects developed after the year 2000 have an average cost overrun of 33 percent and an average schedule overrun of 18 percent. While schedule overruns appear to have reduced compared to previous decades, there has been no significant reduction in cost overruns (Plummer Braeckman, Disselhoff, and Kirchherr 2019). Dam projects also tend to suffer from so-called geological surprises, where underground conditions, especially for projects involving extensive tunneling, are much less favorable than investigations suggested they would be.

Future hydrological uncertainty is a major challenge for the design and operation of dams as well. While an opportunity for some regions, given the expectation of more runoff, climate change is increasing the hydrological risk for new and existing dams. This can include projected changes in hydropower production or risks to the infrastructure and downstream communities posed by large floods, as noted in chapter 1. In designing new water infrastructure, the approach of relying on the historical hydrological record under the assumption of hydrologic stationarity is no longer adequate. Whether it is greater flood risks or the possibility of lower inflows, climate uncertainty should factor into the design and reoperation of any dam or water storage facility. This can be achieved through climate sensitivity screening in the planning phase, possibly followed by robust climate risk analysis during preparation. Climate risk analysis to find the most robust investments involves stress-testing project designs and alternatives against a multitude of possible climate futures. Referred to as "decision-making under uncertainty" or "robust decision-making," this process avoids trying to select the most probable climate futures; instead, it identifies those investment options that perform most optimally under a range of scenarios (Hallegate et al. 2012; Rodríguez et al. 2021).

2.3.6 Smaller-Scale, Built Infrastructure

Beyond traditional dams, large and small, societies have engineered a diversity of water retention structures to suit their needs. The ancient tank system of Sri Lanka (see annex 8A) is one example, whereby small artificial reservoirs, or *tanks,* were built in cascades according to the natural topography of the land. Connected to one another and to larger reservoirs by canals, they support irrigation and other water supply needs of the communities around them. Similar tank structures can be found in India, some of which are fed by natural springs. They serve a variety of purposes, such as irrigation, water supply, and religious and cultural purposes. In other parts of the world, smaller-scale water storage might take the form of elevated storage reservoirs, forming part of the potable water supply system in cities and towns. Like dams, these storage solutions tend to be public or community-scale facilities, whereas in private homes and businesses, it is increasingly common to find lightweight manufactured tanks, sometimes deployed in modular systems. These more decentralized forms of water storage can avoid some of the negative externalities of larger, centralized storage reservoirs, but they may provide limited storage and, in some cases, can have higher per-unit costs (van der Zaag and Gupta 2008).

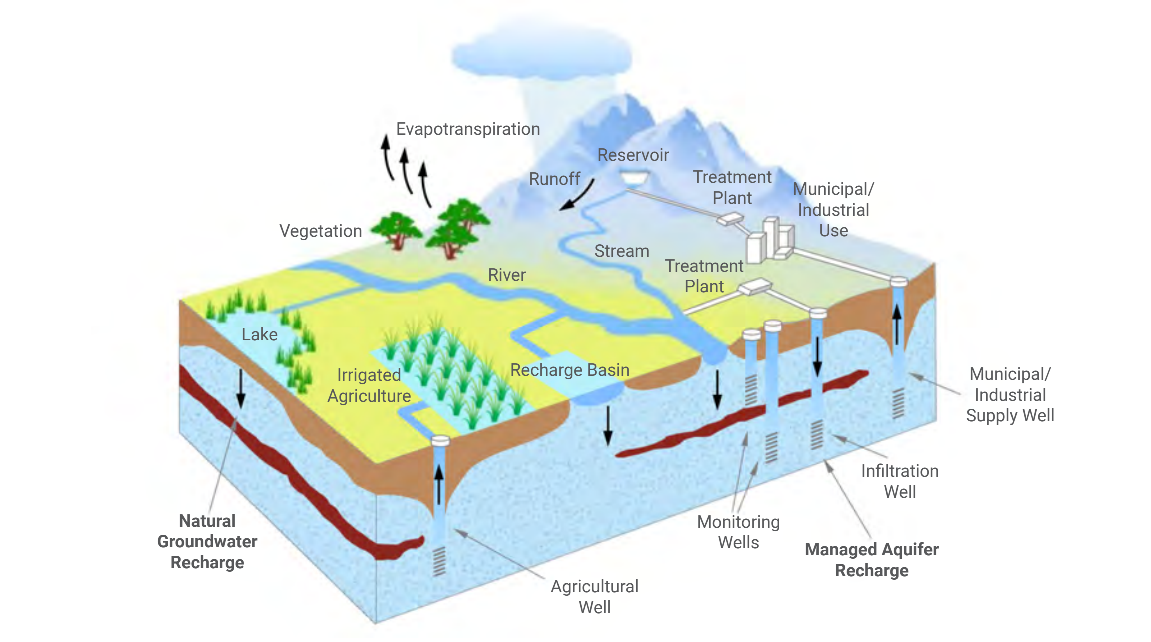
2.4 HYBRID STORAGE

Hybrid storage combines both natural and built storage options and contains built elements that interact with natural features that seek to enhance their water-related ecosystem services (WWAP 2018). Hybrid storage options include MAR (box 2.5), urban sponges, paddy fields, flood channels, sand and subsurface dams, ponds and haffirs, and polders and dry dams. Like purely green or gray storage, hybrid storage is often multifunctional and can provide co-benefits outside of the primary sector beneficiaries (e.g., flood control, sediment control, water purification, and recreation). This type of solution has been increasingly implemented to enhance water availability under various climatic, geographic, and socioeconomic

BOX 2.5 Managed Aquifer Recharge

Managed aquifer recharge (MAR)[a] is a useful water management tool in a variety of areas to enhance the quality and increase the quantity of water supply. It is a nature-inspired solution that intentionally recharges aquifers with surface water for later use or environmental benefits (figure B2.5.1). MAR can be a less expensive and less environmentally damaging option to boost water supplies in a region compared to constructing large surface storage.

FIGURE B2.5.1 Managed Aquifer Recharge in Water Resources Management



Source: INOWAS n.d.

Apart from direct benefits of increasing the availability of water in an aquifer, reducing evaporation, and helping to improve or maintain the water balance, MAR can provide other community and environmental benefits. For example, MAR projects that utilize stormwater in urban areas can help mitigate floods and improve water quality of local streams and coastal water bodies. MAR can also be used to improve groundwater quality by controlling saltwater intrusion or by helping in diluting existing groundwater of higher salinity and thus making it slightly better for irrigating crops. MAR can also help in providing extra water for environmental flow and groundwater-dependent ecosystems. However, if not managed properly, MAR can cause groundwater pollution due to recharge with low-quality surface water.

Depending upon the local hydrogeology, needs, and other factors, a variety of methods and configurations can be used to recharge aquifers. For example, open infiltration ponds can be used to recharge unconfined aquifers, while injection well techniques like aquifer storage and recovery (ASR) can recharge aquifers that are more deeply confined (CSIRO n.d.). Site selection for MAR activity is important to ensure that there is a sufficient supply of water, and that the soil and aquifer are sufficiently permeable. Table B2.5.1 lists the different typologies of MAR systems.

[a] MAR is also known by other terms such as artificial recharge, water banking, and groundwater replenishment.

(box continues next page)

BOX 2.5 Managed Aquifer Recharge (cont.)

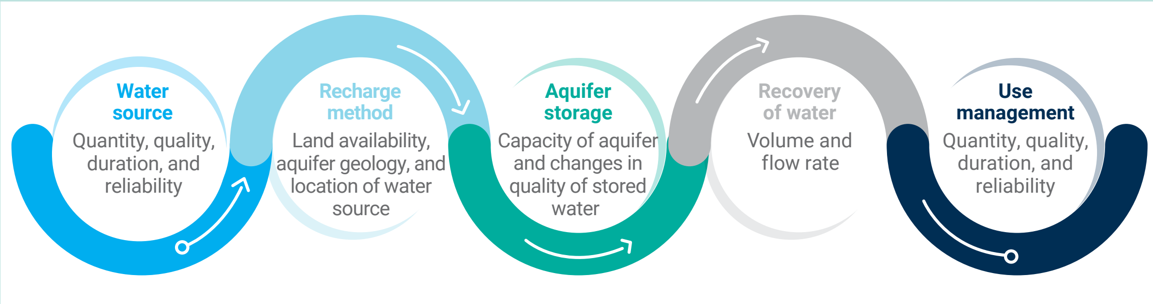
TABLE B2.5.1 Managed Aquifer Recharge Typologies

	MAR METHODS	SPECIFIC MAR METHODS
Techniques referring primarily to getting water infiltrated	Spreading methods	Infiltration ponds (soil aquifer treatment)
		Flooding
		Ditches and furrows
		Excess irrigation
	Induced bank infiltration	River/lake bank infiltration
		Dune filtration
	Well, shaft, and borehole recharge	Deep well injection: aquifer storage and recovery and aquifer storage, transfer, and recovery.
		Shallow well, shaft, pit infiltration
Techniques referring primarily to intercepting the water	In-channel modifications	Recharge dams
		Subsurface dams
		Sand dams
		Channel spreading
	Runoff harvesting	Rooftop rainwater harvesting
		Barriers and bunds
		Trenches

Source: INOWAS n.d. adapted from IGRAC 2007.
Note: A thorough description of each one of the MAR typologies can be found at INOWAS n.d.

The sound technical design of a MAR system is crucial to ensure the system will operate effectively in the long term. Five main, site-specific questions to consider at the project planning and design stage are (a) What is the source of water? (b) How will water be transferred and stored in the aquifer? (c) How will the aquifer properties affect the stored water? (d) How will water be recovered from the aquifer for subsequent use? and (e) How will the end use of recovered water be managed? (NRC 2008) (figure B2.5.2). The consideration of these questions requires a detailed field investigation and stakeholder consultations. It is also important to ensure there is adequate capacity to operate the MAR system, especially with more advanced MAR technologies that use injection wells.

FIGURE B2.5.2 Managed Aquifer Recharge Considerations



Source: Adapted from NRC 2008.

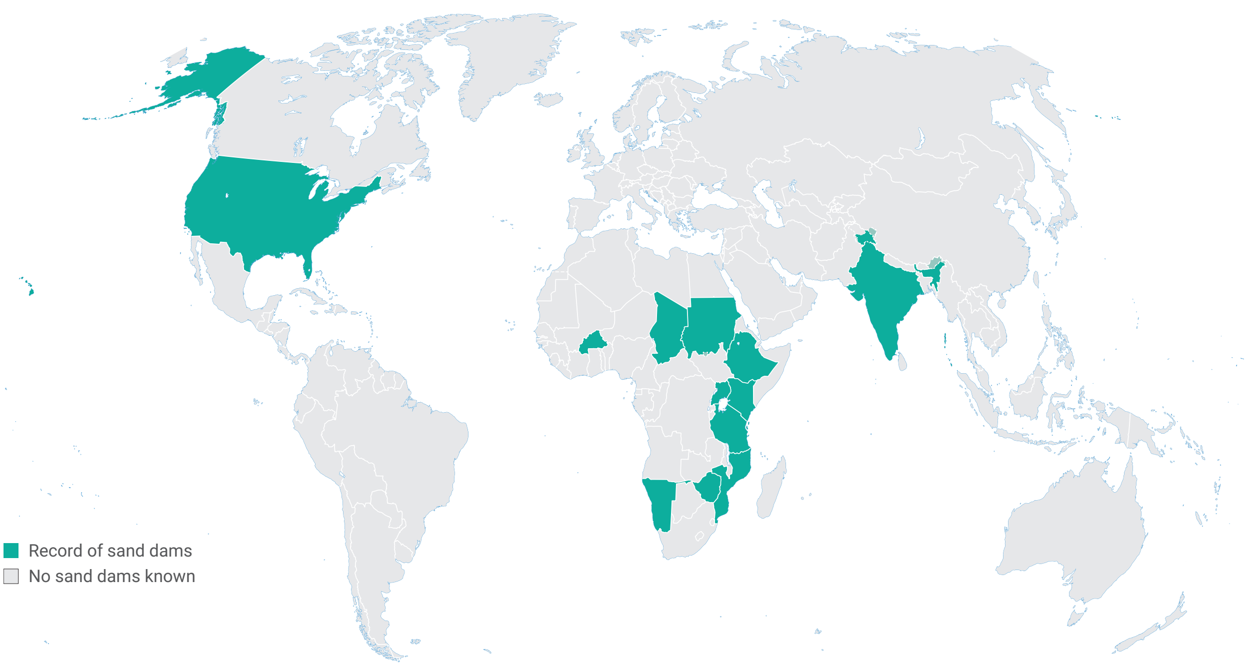
conditions. For example, spurred by nongovernmental organization (NGO) support, sand dams have been used in many locations over the past 25+ years (map 2.5) (Ritchie, Eisma, and Parker 2021).

Hybrid storage can increase the reliability and productivity of natural storage. Ecosystem restoration or newly constructed natural infrastructure can take time to reach its full potential. As organisms need to take hold, these ecosystems will grow stronger as they mature. A hybrid storage solution can help communities to use built infrastructure to provide benefits in the interim while natural infrastructure is established. Built infrastructure has the potential to be protected by natural infrastructure (Sutton-Grier, Wowk, and Bamford 2015). For instance, vegetation and temporary storage in urban areas can contribute to the protection of stormwater systems from collapse and overflows, mitigating floods in dwellings. This helps cities to release less flood water through the gray infrastructure drainage system that can overburden wastewater treatment plants (Busayo et al. 2022).

Hybrid storage has the potential to be implemented in areas where natural storage alone would not be viable (Sutton-Grier, Wowk, and Bamford 2015). To create the space for hybrid infrastructure and river restoration, many cities are considering or even implementing major infrastructure projects and removing key assets like major highways or housing developments (Sutton-Grier, Wowk, and Bamford 2015). Such is the case in the Cheonggyecheon stream restoration in Seoul, Korea, which involved demolishing an elevated freeway and uncovering a section of the stream within the built environment. This greening of the infrastructure added storage capacity and provided protection from a 200-year storm event during the rainy season, as well as providing recreational opportunities during the dry season. As a result, land values increased in the surrounding area by 30–50 percent (Landscape Architecture Foundation 2014).

However, hybrid solutions can pose some inherent challenges to be considered by planners and designers. The life cycles of green and gray infrastructure are distinctly different (Andersson et al. 2022). Another central difference is that societal functions of green infrastructure are characterized by regenerative processes—yet they need to be protected to allow this to occur; gray infrastructure needs substantial financial investment to stave off material decay in order to uphold its functions (Andersson et al. 2022). The knowledge and

MAP 2.5 Prevalence of Sand Dams



Source: Adapted from Ritchie, Eisma, and Parker 2021.

resources needed to work with them are often embedded in different, disconnected sectors. These differences present a challenge, but at the same time, they are a source of diversity that can be used to build layers of resilience (Andersson et al. 2022).

2.5 CONNECTIONS ACROSS PHYSICAL AND SOCIOECONOMIC SYSTEMS

2.5.1 Most Storage Is Interdependent

Freshwater storage facilities—whether natural, built, or hybrid—generally rely on the same water, which often flows between them over time. The concept of how water moves constantly through the whole water cycle applies to storage. For example, the same drop of water might first be stored in a mountain glacier, then in a downstream wetland, then in an aquifer, before emerging into a river and being stored in a dam, then in urban water tanks, and so forth.

Storing water impacts the hydrological system, and it is necessary to understand the dynamics of the system to ensure that investments in storage achieve the desired goals. For example, investments aimed at increased rainwater harvesting via terracing will increase local soil moisture storage but reduce runoff, thereby potentially reducing downstream wetland or reservoir storage. Similarly, installing a dam upstream of aquifer recharge zones may reduce downstream groundwater, or change the timing of water availability across seasons. These consequences may be desirable or undesirable depending on the local context but need to be understood and planned for.

Storage investments and management must be coordinated across the hydrological system to achieve aggregate goals. Since the development and management of one storage facility may impact other storage facilities, it becomes necessary to plan and coordinate at the relevant system scale, often the basin level. Similarly, it may be necessary to build connections between storage types to allow for more deliberate control of the storage system. Integrated planning and management is not only a technical process, but, given the likelihood of multiple stakeholders seeking multiple outcomes, it becomes a social, political, and economic one as well.

2.5.2 Embedded in Larger Systems

A hydrological system of storage is often embedded in broader social, environmental, and economic systems. The storage system in any given place is part of a broader hydrological system, including precipitation and flows of water, which in turn is part of broader environmental systems that rely on the water and influence its behavior. The fact that humans are constantly using and consuming water, and usually relying on stored water when they do so, also means storage systems are part of broader social and economic systems that shape and are shaped by them. Not all water storage solutions will work in all settings and will depend on geography, population density, hydrology, and network connectivity, among other factors.

Social and economic preferences shape water storage needs, including the nature of the service required, willingness to pay, necessary levels of reliability, and risk tolerance. For example, farmers practicing rainfed irrigation will focus on rainwater harvesting to increase soil moisture, while those practicing irrigation will want storage that enables controllable flows of water to their farms; urban consumers want relatively small amounts of water literally on tap, while hydropower operators want large volumes of water stored for future needs. Different types of users need different levels of reliability in their service and have different tolerances for risk. Industries that require 100 percent reliability will have a different level of willingness to pay for storage services and a very limited tolerance for risk. The Integrated Storage Planning Framework introduced in chapter 3 includes consideration of the water service requirements of users, which can help to differentiate what types of water storage or broader water management measures may be needed to meet their requirements.

2.5.3 Managing Risks at the System Scale

Each type of storage is subject to performance risks. Risks to the reliability of water storage services may take several forms, including water quantity, quality, location, and timing. Landscapes may become degraded, reducing soil moisture and slowing aquifer recharge. Droughts will impact small surface storage more rapidly than large groundwater deposits. Public multipurpose reservoirs may be subject to more stakeholder conflict than privately owned single-purpose reservoirs. Water quality may be more easily controllable in local reservoirs than aquifers.

Multiple and different types of storage are likely to provide more reliable storage services than individual facilities. The types of risks are numerous, and while they may be connected by large events like floods or droughts, they are not necessarily immediately correlated. Droughts will impact different types of storage over very different timescales, for example. Many storage risks are therefore best managed at the system scale. For hydropower in particular, system-scale planning can help stakeholders find better-balanced solutions with lower impacts and conflicts and can help governments avoid burdens or delays, thereby delivering better development outcomes (TNC et al. 2016).

2.5.4 Addressing Challenges and Scaling Up

Storage gaps need to be addressed—but not always with more storage. The two chapters so far have described the importance of freshwater storage, the risk of growing storage gaps, the variety of storage that exists, and why it needs to be managed as a system. Chapter 3 describes potential approaches to filling the storage gap, starting with the need to consider the full range of choices—including demand management, alternative supply mechanisms, and storage—that may be required to fill identified storage gaps at the local level.

A supply-side only approach to storage risks encouraging an unsustainable demand-side response. Some surpluses in storage may be very desirable from a long-term development and risk management point of view—particularly given that storage can take a long time to develop. However, there is a consequential risk that new activities will arise to take advantage of this storage surplus, which may or may not be economically justifiable from a longer-term perspective. Several cases around the world have illustrated this two-way relationship between storage demand and supply: Demand creates supply, but supply can also create demand (Damania 2020). From a policy perspective, it's always important to focus on how storage use will be regulated and efficiencies incentivized, rather than simply on storage supply supplementation. This can include valuation and pricing of water, as well as of the storage services themselves.

If additional storage services are needed, they may be addressed through rehabilitating, reoperating, or retrofitting existing storage, as well as through raising new storage. These measures are not simply about physical construction but also around the policy and institutional environments that shape storage services and the behavior of storage users—including reform. Chapter 3 outlines an approach to addressing these issues in a systematic way.

ENDNOTES

1 Built, or gray, infrastructures are *"built up, engineered and physical structure[s], often made of concrete or other long-lasting materials, that mediate between the human, built up system and the variability of the meteorological and climatic system"* (Depietri and McPhearson 2017).

2 For further details about these solutions, please refer to the Glossary.

3 A NEW FRAMEWORK FOR INTEGRATED STORAGE PLANNING

The new Integrated Storage Planning Framework presented in this report aims to begin to address the storage gap in a way that is efficient while being cognizant of the environmental and social risks that are inherent in water resources planning and development. One of the main purposes of the framework is to provide a systematic process for early identification and consideration of potential opportunities and trade-offs that are often only given attention after significant sums have been invested in project preparation and some design choices have already been made. Given that storage needs and dynamics vary greatly by location, this framework acts as a guide and will need to be adapted to each individual setting, depending on needs, data availability, and how much storage planning has already taken place.

This framework—introduced in this chapter and elaborated on with step-by-step instructions in part II of this report—is primarily targeted at government officials and others involved in policy development and strategic planning in water-dependent sectors, as well as the development practitioners who support project- and sector-level interventions to improve water security and water storage availability. It can be used flexibly to suit specific challenges: Water managers can conduct a quick desk review or guide a longer, iterative planning process with engagement of stakeholders across sectors.[1]

3.1 A PROBLEM-DRIVEN, SYSTEMS APPROACH

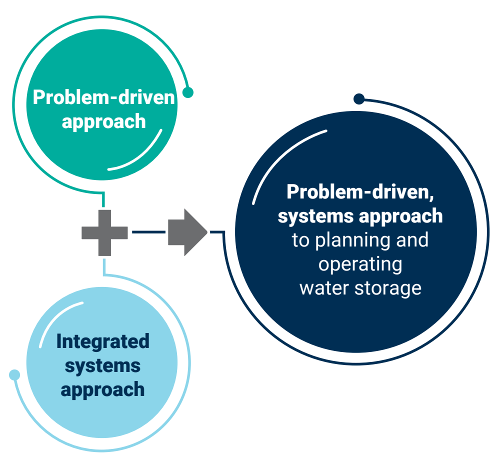
Integrating multiple approaches offers additional solutions to address the water storage gap. The storage planning framework supports decision-makers as they strive to answer the questions:

- What interventions do I need to put in place to meet my water security goals—while minimizing negative impacts?
- What forms of water storage development and management are part of the solution?

Moving beyond the status quo, where storage planning often occurs mostly at a project level, this integrated framework combines two approaches: *a problem-driven approach* and a *systems approach* (figure 3.1). A combined problem-driven, systems approach to planning and operation of storage is a more strategic and robust alternative to conventional planning, as it considers interconnected water resources management components across storage types, scales, and user needs.

This combined approach to water storage planning fits within broader integrated water resources management (IWRM), with the river basin as the primary frame of reference. However, this approach builds on IWRM, with focus on concurrent joint planning around specific water-related

FIGURE 3.1 Planning and Operating Water Storage



Source: Original figure for this publication.

problems to be solved, thorough storage or other management measures.

3.1.1 Problem-Driven Approach

A problem-driven approach entails defining the challenge and identifying the underlying problems that require a solution. The concept is used across numerous fields, where the solution designer (software developers, engineers, biological or pharmaceutical design teams, social scientists, among others) (Fritz, Levy, and Ort 2014) delve into and define the underlying problem that must be solved rather than starting from a set of design specifications, for example, impacts from disasters such as floods and droughts, inadequate water supply for household consumption, agricultural or industrial production, reduced electricity generation, potential threats to biodiversity, environmental flows and ecosystem services, reduced transportation for goods and people, and limiting recreational opportunities. From these identified problems, targeted development objectives can be formulated.

The underlying problems to be addressed, the constraints and challenges to address them, and their potential negative consequences should be carefully defined to identify the most appropriate solutions in the given context. This allows for the comparison of a range of possible solutions that may be evaluated to identify the most feasible path to achieving the stated development objectives. Applying this process to the example of reducing the impacts of floods, the solutions could range from built water storage measures such as reservoirs, to nature-based storage solutions such as upstream wetlands restoration, to non-storage solutions like drains, to non-water solutions like zoning or insurance, as well as management options such as reoperation of existing infrastructure. The most effective response may well be a combination of storage, non-storage, and non-water measures.

3.1.2 Systems Approach

A systems approach takes into account necessary enabling systems and services, the roles played by different parts of the system, and the relationships between those parts with respect to the overall behavior and performance of the system (box 3.1). A water resources management system is usually defined at the basin scale and can include the (a) natural sub-system, including hydrology and relevant water management infrastructure, (b) the socioeconomic sub-system, including all water-related human activities (including energy, irrigation, etc.), and (c) the administrative and institutional sub-system that plans, builds, operates, and governs water management systems (Loucks et al. 2017).

A systems approach can leverage interconnections to build integrated approaches to development problems, integrating geographic, socioeconomic, and institutional factors. For example, a connected water storage system can support integrated flood and drought management by transferring flood excesses to periods of scarcity through measures such as managed aquifer recharge fed by diverted floodwaters, as is being done with the Underground Taming of Floods for Irrigation (UTFI) approach in the Ganga Basin. Integrated flood and drought management is also supported by forecast-informed reservoir operations (FIRO) as in Lake Mendocino, California (see case study, chapter 8).

BOX 3.1 Systems Approaches: Green and Gray Planning

The City of Cape Town experienced a 1-in-a-590-year drought from 2015 to 2018, which demonstrated its limited capacity to access other sources of water outside of water storage. After solving the short-term water scarcity issue through reducing water demand and reallocation of water in storage (which required underlying water rights and robust water management systems), Cape Town developed a new water strategy that will add other sources of storage and water to its portfolio to relieve overdependence on its current systems. This includes both built infrastructure in the form of desalination plants and wastewater reuse facilities as well as green storage through the increased use of groundwater and groundwater storage. This will be combined with increasing the resilience of the regional water storage system to create an integrated, multiple water source approach to mitigate future drought impacts. (For details, see case study, chapter 8.)

3.2 THE INTEGRATED STORAGE PLANNING FRAMEWORK

Bringing together both the problem-driven and systems approaches into a single framework leads to potential solutions not considered by one approach alone. As an options assessment, the framework proposed is intended to be an early planning exercise that puts key strategic considerations in a form that helps stakeholders understand and assess the range of options available, how and why they are interconnected, the pros and cons of different combinations of measures, including negative impacts, and how non-storage solutions may fit among the available options or offer alternatives. It enables a more informed decision about which combinations of storage are worth further exploration and whether they should be implemented in parallel or in a phased manner.[2]

The framework is organized in three stages: (1) a needs assessment to define the problem; (2) a definition of the system and potential solutions; and (3) a decision-making process considering a range of scenarios and uncertainties (figure 3.2). The first stage includes defining the development objectives, such as access to safe and affordable drinking water, and the related water service requirements to meet those objectives. It then characterizes the current water resources system (including storage) and other systems that may need to be considered (energy, agricultural markets, etc.). Following that, it systematically identifies additional potential options and models how those options, in different combinations or scenarios, would result in changed levels of service. This includes options other than storage, as well as a range of storage options, from green to gray, small and large. It encourages consideration of many modalities of intervention, from rehabilitating existing storage, to retrofitting it for different uses, to reoperating storage, to raising new storage or engaging in other sectoral reforms. The last major step in the framework is to use decision criteria to guide the choices for further study.

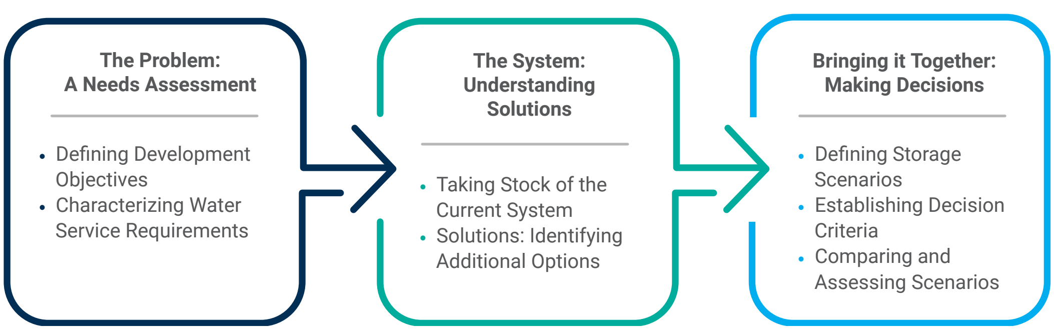
Underlying problems in the system can be translated into development objectives, and these objectives can be better defined by understanding the water service requirements that are needed to achieve them. The term *water service requirements* is used as a broad term, describing the supply and control of water needed to support the development objectives and outcomes identified during the needs assessment stage. These could include:

- Water supply for drinking and domestic use, crops and livestock, industry, etc., expressed as an amount
- Flood protection and attenuation of excess flows for disaster risk reduction
- Control of flow and level for navigation, hydropower generation, or recreation and cultural services
- Environmental flows for ecosystem preservation and restoration (including prevention of saline intrusion)

The volumetric, temporal (when and how often), and geographic dimensions of the requirements should also be considered.

Water service requirements can be more specifically described with key parameters that provide for comparison of different water management options, including storage, in terms of quality of service. These parameters, referred to as *water service attributes* in this framework, are (a) reliability; (b) controllability; (c) adaptability; (d) vulnerability; and (e) quality (table 3.1).

FIGURE 3.2 Integrated Storage Planning Framework Stages



Source: Original figure for this publication.

TABLE 3.1 Water Service Attributes

	WATER SERVICE ATTRIBUTE	DEFINITION	PERFORMANCE INDICATOR	UNIT (EXAMPLES)
1.	**Reliability**	Degree to which water management options consistently succeed in serving all intended purposes	—	—
1a.	Assurance levels	Performance reliability of the water management option	Average time between consecutive performance failures (predicted probability or historic)	Years, months, days
1b.	Impact of unreliability	Magnitude of performance failure if underlying option fails to support service delivery	Size of impact if option fails to deliver on intended purpose (can be graded by percentage of failure)	Hectares of crop lost, financial/economic cost
2.	**Controllability**	Degree to which water management may be controlled or operated for intended purposes	—	—
2a.	Volumetric control	Degree to which volume of water can be controlled	Least amount of water that may be released	Cubic meters
2b.	Geographic control	Geographic area that can be serviced by underlying water management option	Service area that can be supported by the option	Square kilometers
2c.	Temporal control	Frequency with which underlying water management option can be re-mobilized for service delivery	Average time needed between consecutive operations or for recharge	Years, months, days
3.	**Adaptability**	Ability to adjust or modify water management option to new conditions, uses, or purposes	Number of other uses or conditions the water resources management option could be modified for	Number
4.	**Vulnerability**	Susceptibility to and magnitude of potential damage from hydroclimatic hazards	—	—
4a.	Physical vulnerability	Susceptibility to flood and drought hazards (influenced by design parameters, location, and operating condition)	Likelihood of significant damage or total system failure	Low, moderate, substantial, high
4b.	Magnitude of vulnerability	Magnitude of consequences of significant damage or total system failure	Extent of potential impact	Hectares of crop lost, kilowatt-hour of hydropower foregone, potential loss of life, financial or economic cost
5.	**Quality**	Degree to which freshwater is free of contaminants that negatively affect its uses	—	—
5a.	Salinity	Amount of dissolved salts in the water body or source	Concentration of dissolved salts	Conductivity values
5b.	Pollution	Presence of pollutants from point and nonpoint sources	Concentration of pollutants such as heavy metals, harmful chemicals, bacteria, nutrients, and oxygen-depleting substances	pH values, total dissolved solids levels, biological oxygen demand, quantitative mass measurements
5c.	Turbidity	The relative clarity of freshwater	Concentration of suspended sediment	Quantitative mass measurements

Source: Original to this publication.
Note: — = not applicable.

TABLE 3.2 Summary of the Integrated Storage Planning Framework

		DIMENSIONS	
		TECHNICAL CHARACTERIZATION	**STAKEHOLDER AND IMPACT ANALYSIS**
STAGE 1	**THE PROBLEM: A Needs Assessment. Characterize the problem, stakeholders, and water service requirements**		
	1.A Defining development objectives	• What are the development objectives for the system? • Are the right priorities set in pursuit of sustainable development and inclusive growth?	• Who has the problem and who may be part of the solution? • How will the solutions to the various problems identified be agreed and advanced?
	1.B Characterizing water service requirements	• What are the water service requirements for meeting development objectives in the system? • What are the priority service attributes desired for the water service requirements?	• Which stakeholders' water service requirements are not met? • What are their vulnerabilities and opportunities if water service requirements are met?
	Stage 1 Outputs: A needs assessment that specifies the water service requirements for the system developed through decision criteria and characterization of stakeholder interests, capabilities, enabling environment, and alternatives		
STAGE 2	**THE SYSTEM: Understanding Solutions. What are the current water management and storage measures in the system? What additional measures are possible in the system?**		
	2.A Taking stock of the current system	• What are the water security measures, storage and non-storage, in place in the current system? • What is the performance against relevant criteria, including the ability to meet the system's water service requirement attributes, infrastructure functionality, sustainability and condition, and benefits that will be quantified and compared during the analysis of options in Stage 3?	• To what extent does the existing water management system engage and benefit stakeholders? • What are stakeholder incentives, capabilities, and institutional systems to determine feasibility of options to improve existing water management systems? • How are existing water security and storage systems used/not used for their intended purpose or how they may serve alternative purposes? • How do existing storage systems positively or adversely impact (or exacerbate vulnerabilities for) stakeholders? • How do existing storage systems and their operations contribute to environmental sustainability?
	2.B Solutions: Identifying additional options	• What are the additional options for meeting the water service requirements of the system? • How can you get enhanced performance from the current system and what are the opportunities for developing new options? • Are there non-water alternatives to problems identified in the system? • How do the options contribute to the desired water service requirement attributes?	• What are stakeholder interests related to additional options considering how they relate to interests in the current system and as they may relate to other new options?
	Stage 2 Output: A model of the system, a set of potential solutions, and a stakeholder map		
STAGE 3	**BRINGING IT TOGETHER: Making decisions. Storage planning, management, development, and operations**		
	3.A Defining storage scenarios	What are the different storage scenarios?	Engage stakeholders in a structured decision-making process
	3.B Establishing decision criteria	What are the different decision criteria that should be in place to assist with the decision-making process?	
	3.C Comparing and assessing scenarios	What is the best solution to address the water security issue?	
	Stage 3 Output: Ranked list of storage solutions for further study and preparation		

Source: Original to this publication.
Note: Feasibility study, ESIA, and/or further preparation and design of selected storage measures, as needed.

The framework presented here is not only a technical review but is ideally an opportunity to shift the conversation on freshwater storage so that it includes a more diverse group of stakeholders, thereby allowing for a broader set of potential solutions. The needs of and potential impacts on different stakeholders, including the environment, are explicitly taken into account at each stage of the framework. Starting in the first stage, the identification and mapping of different stakeholders is an essential task. In the second stage, the framework includes characterization of how different stakeholders may benefit or be disadvantaged by potential changes to the system as well as identification of potential risks and opportunities. In the third stage, during the comparison of different scenarios, stakeholder interests and environmental considerations become more specific, and ideally quantified, as they become part of the decision-making criteria used to determine the way forward.

While the process outlined in the framework is fundamentally public sector-led, it recognizes the importance of the private sector and civil society in planning, developing, and operating water storage investments, and highlights areas where they have specific roles to play. While a multi-stakeholder planning process would be at the expense of expedient decisions, such processes are proven to increase trust, stakeholder satisfaction, transparency, and performance in the water sector (Fox 2015; Water Witness 2020). These conditions enable greater ownership and buy-in from stakeholders, which could reduce delays in implementation. Each situation should be tailored appropriately to the needs of the stakeholders to create sustainable and efficient storage capacity for both present and future needs. It is not meant to be exhaustive, but it provides tools and resources to arrive at better storage outcomes.

The framework ties together the three stages of establishing the problem, information gathering, and decision-making, while incorporating stakeholder engagement and key questions to address and develop integrated solutions at the system scale (table 3.2). For those wishing to better understand each phase of the framework, or apply the framework, chapter 7 of this report elaborates each stage of the framework, including key questions each stage should ask and answer, and provides some guiding questions for use when undertaking an options analysis using this framework as a tool. Additionally, examples are provided to spotlight technical tools and innovation that may help in storage planning.

ENDNOTES

1 This framework is not intended to replace normal project preparation studies, nor serve as an additional step that must be undertaken before any storage intervention can be designed. Rather, it provides a planning exercise that can be undertaken to identify opportunities for improved storage planning and management. The framework is presented as an opportunity for stronger development outcomes, as a new good practice, but is not a World Bank requirement for project identification or preparation.

2 The framework deliberately casts a wider net than a typical options assessment—which is often already focused on different permutations of the same technology— to ensure more potential solutions and counteract the natural biases planners may have for one kind of approach over another. An earlier attempt by the Dams and Development Project (UNEP 2011) to introduce a Comprehensive Options Assessment on Dams and Their Alternatives shared many of the same principles as the framework put forward in this chapter, but this framework is borne from a technology- and sector-neutral perspective on water storage with greater emphasis on the potential of nature-based solutions to be used conjunctively with built infrastructure.

4 INSTITUTIONALIZING INTEGRATED STORAGE PLANNING

This chapter highlights institutional issues that will need to be addressed to undertake a problem-driven, systems approach to water storage planning and management. As the services provided by water storage and the problems water storage addresses can involve a range of sectors and institutions, new institutional arrangements and mandates may be needed to engage in more effective storage operation and management. This is the fifth "R" in storage management—reform. In other cases, existing mechanisms such as basin planning processes may be activated and adapted.

In most places, an integrated framework will need to be implemented with imperfect information and in the face of resource constraints. In an ideal situation, there would already be a well-developed regulatory and institutional framework that clearly lays out roles and responsibilities and sets guidelines that support the assessment and implementation of water storage options. Ideally, the regulatory framework would include protections for natural storage like wetlands, rivers, and forests, as well as for water towers, riparian areas, and critical groundwater infiltration areas. There would be sufficient data of good quality upon which to base basin-level studies that scope options and potential risks and opportunities; sector plans would be informed by cross-sectoral linkages; and adequate resources would be available for detailed investigations and project-specific analyses. However, the reality is that many planning and investment decisions are made—and indeed have to be made—in the context of financial and human resource constraints, as well as gaps in information. This chapter focuses on how to apply the storage framework given these challenges.

The challenges in implementing this problem-driven, systems approach to water storage planning will, in many ways, be the same as those that encumber the implementation of integrated water resources management (IWRM). Despite growing awareness of IWRM principles among policy makers and water managers, the implementation of IWRM is progressing at only half the rate that is needed to achieve Sustainable Development Goal (SDG) target 6.5 on IWRM implementation. According to the 2021 progress update, 107 countries were not on track to have sustainably managed water resources by 2030 (UN-Water 2021). There are many challenges for IWRM implementation, which also extend to managing water storage in a more integrated way. Among these are lack of data, coordination challenges, misaligned incentives, institutional capacity issues, and funding. The problem-driven, systems approach is designed with some of these challenges in mind.

While institutional barriers constrain the use of integrated planning approaches, taking a problem-driven, systems approach to storage can offer better outcomes compared to siloed development approaches. Water storage planners must strive to make better storage decisions while knowing that perfection is not attainable. The following section explores many of the institutional challenges and considers lessons learned on how to best manage them.

4.1 DATA AND ANALYSIS GAPS

Hydrological, geological, and socioeconomic data as well as analytical tools for interpretation are key ingredients to developing a good understanding of the current water storage system and what additional options may be feasible to meet storage needs. Traditionally, much of this data is collected by in situ instruments and field surveys, which require adequate physical infrastructure and a skilled workforce. In low- and middle-income countries, there are often significant gaps in hydrometeorological networks and technical skills. Similar challenges exist in wealthier countries due to difficult-to-traverse terrain or where lack of investment has led to the degradation of older systems.

Where data exists, there may be analytical gaps that hinder its use in decision-making. Data must be collected, stored, analyzed, and interpreted to provide useful input into decision-making processes. Models and other analytical and visualization tools transform raw data collected into actionable information that can be communicated to those with the power to act on it. Due to the complexity of the natural and socioeconomic systems implicated in water storage decision-making, these tools are often highly customized and require extensive training to use, and if developed with proprietary software, can be expensive to maintain, especially in low-income environments.

In the current information age, the rise of earth observation data, machine learning, and advances in computing have resulted in a proliferation of free and low-cost datasets, and open-source analytical platforms and modeling tools that are helping in closing information gaps. Today, some of these resources are robust enough to support improved decision-making as stopgap measures while investments are being made in higher resolution on-the-ground data collection—though they still require validation and calibration with ground data. Increasingly, however, they offer complements to—or even lower cost alternatives to—traditional data collection methods (box 4.1).

Satellite images can be a powerful tool in facilitating the process of closing information gaps. The use of remote sensing for operational purposes (planning, design, monitoring, or operating) in water resources management is a fast-growing field. Remote sensing can provide spatially distributed and timely observations, and very large amounts of this data is freely available and open to the public; however, processing and interpretation of data is required to ensure proper monitoring and reporting (García et al. 2016). Validation and calibration with field-level data is usually needed. For operational purposes, services can be developed to automate and process images, presenting an approach to observe water storage dynamics (World Bank 2021d).

Remote sensing plays an important role in providing the information needed to meet water challenges. García et al. (2016) present available data by remote sensing that can be used to fill the gap where ground data is scarce. It includes a guide for determining the data needs and an overview of relevant variables provided by earth observation for each water challenge, indicating the most suitable sensors rearranged to focus on spatial and temporal resolution. For instance, for identifying and monitoring water storage, spatial resolution is usually the most important factor and high resolution may be required, whereas slow water dynamics mean that a moderate frequency is likely to be required. High-resolution sensors[1]—either optical or radar—can be used to identify the surface area of a small dam (World Bank 2021d). Measuring surface water elevation using earth observation technology can provide estimates of changes in total water volume in reservoirs and other water storage systems such as wetlands (García et al. 2016).[2]

BOX 4.1 Working in Data-Scarce Environments: Example from the Western Sahel Region

How do you plan water storage in regions where data is scarce and capacity is constrained? How do you identify appropriate small-scale water storage solutions, at scale, for communities dispersed across the landscape?

With Africa's population growing at the highest rate in the world, the availability of water resources is decreasing, not only in relative (per capita) terms but also in absolute terms. The actual storage capacity in large dams in most Sub-Saharan basins decreased by 5–10 percent in the 20-year period from 1990–2010 (Wisser et al. 2013). Therefore, it is critically important to look at other modes of reliable water storage, especially small-scale and nature-based solutions. To this end, the World Bank, in collaboration with a consortium of international partners, has supported the development of the Water Harvesting Explorer, a decision-support tool for small-scale water storage interventions planning. The tool was developed initially for the Western Sahel region to provide field-level agency staff and local communities with a starting list of interventions that are “water-appropriate” for any given location.

(box continues next page)

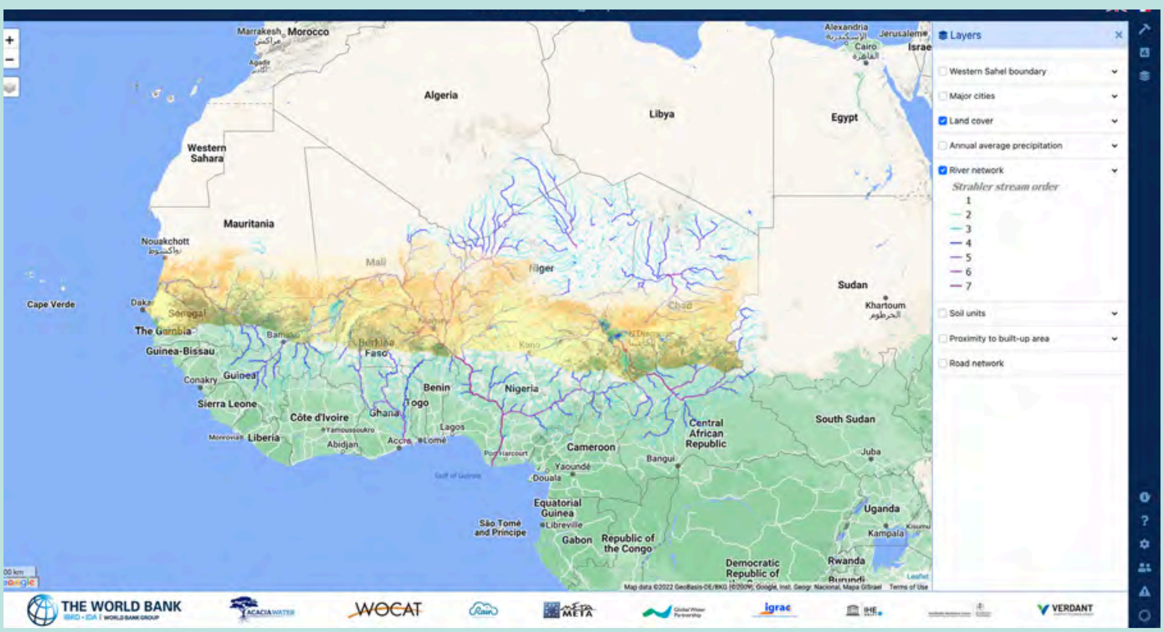
BOX 4.1 Working in Data-Scarce Environments: Example from the Western Sahel Region (cont.)

The Water Harvesting Explorer (figure B4.1.1) provides potential options for water harvesting at any location of interest, based on the local biophysical conditions, including annual precipitation, slope, and land cover. The tool uses global datasets and draws on the World Overview of Conservation Approaches and Technologies Repertory of Sustainable Land Management to suggest a long-list of intervention options, which can then be narrowed down through community consultations and local ground-truthing. The user can click on a desired point on the map and then is shown an illustrated list of potential water harvesting technologies that have been successfully implemented in similar bio-physical conditions. It also provides important information for each of the options, such as technical specifications, specific benefits and limitations, and costs. Information on local socioeconomic conditions can be added by the users to guide the choice of appropriate water harvesting methodologies. In addition, warnings and notifications inform users about any conditions (such as locations in protected areas, erosive settings, etc.) that could change or complicate the intervention.

The menu of options identified by the tool can facilitate the dialog with the local communities, by serving as a starting point for exploring the range of potential solutions to address their water needs. The tool is currently being piloted in a World Bank-supported intervention in Niger, and is being expanded in similar settings in Nigeria, Ethiopia, and Somalia.

The tool is available at https://sahel.acaciadata.com. New features are expected to be added in the future.

FIGURE B4.1.1 Screenshot of the Decision Support Tool "Water Harvesting Explorer"



Source: Water Harvesting Explorer: https://sahel.acaciadata.com.

The problem-driven, systems approach to storage planning is designed to be implementable even in the face of data limitations. It can be used as a desktop exercise, relying on the use of publicly available datasets and tools that facilitate early scoping of options and their associated risks and opportunities. It values local knowledge and robust decision-making approaches that are useful in the face of climate-related changes and other uncertainties.

The phased approach of the framework enables water managers to prioritize the options deserving of more detailed study.

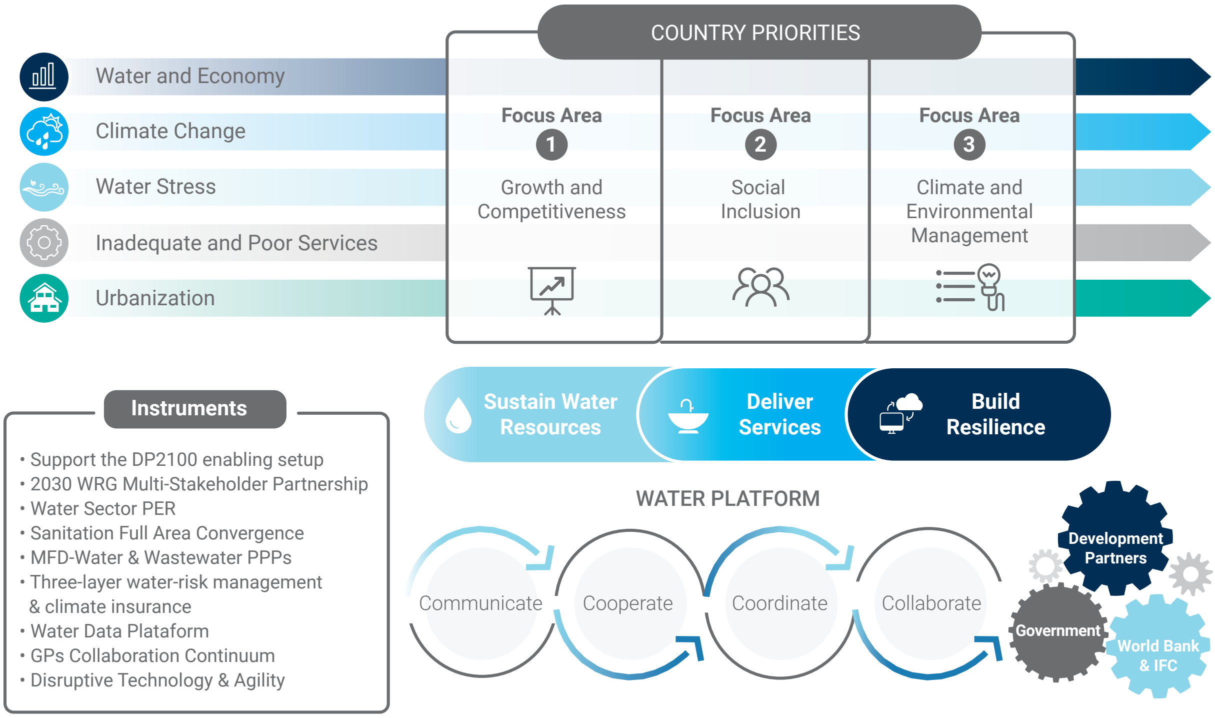
4.2 INTER-SECTORAL COORDINATION

Inter-agency coordination within the water sector is often difficult, even where significant investment has been made in the institutional framework for water resources management. This may be due to overlapping or lack of clarity of institutional mandates at different planning scales, or where a process of decentralization or devolution of responsibilities to the river basin level is underway. Thus, it is important to clarify from the outset who is responsible for leading the water storage planning process and the roles of other key stakeholders. In some jurisdictions, groundwater is governed differently than surface water, with legal regimes often making a distinction between entitlements for flowing water versus for water use on land. This legal or institutional separation does not account for the complex interconnectivity between surface and groundwater systems and can make integrated planning less effective. Moreover, the tendency to treat different water resources and storage projects as isolated endeavors—especially if they are funded through different sources—can lead to duplication, interface challenges, or even set project objectives against one another.

Coordination between the water sector and other sectors may also present a challenge as several different parts of government may be responsible for collecting information and administering policy that affect or depend on water storage. For example, it is common for climatological data to be collected and stored by a meteorological service while information on land use and ownership may be housed within a dedicated land agency. Similarly, data collection and policy implementation related to irrigation, hydropower, or aquatic ecosystems may be the responsibility of an agriculture, energy, or environment ministry, respectively. While it is possible to achieve some degree of rationalization by trying to house the various aspects of water management under the same ministry or agency, it is impossible to do so completely. The EPIC Response Framework (Browder et al. 2021) outlines opportunities that national governments can explore to holistically manage floods and droughts risks with the aim of efficiently reducing the economic, social, and environmental costs of floods and droughts. Several aspects are relevant to integrated storage planning—including coordination over data and forecasts, strategic investments such as those to promote healthy watersheds and green-gray water resources infrastructure, as well as conjunctive groundwater management, among others.

Effective water storage planning necessitates the breaking of sectoral silos and managing the power asymmetries that may exist between water management authorities and those of other sectors. Siloed planning approaches have led to suboptimal storage investments, including single-purpose facilities that can foreclose future opportunities or negatively affect other components in the system. There are, however, effective ways of strengthening inter-sectoral coordination that can produce better outcomes for water storage planning and operation, including the establishment of interagency fora, ensuring appropriate and representative stakeholder composition, and establishing procedures to increase engagement and measure progress. In Tanzania, for example, even though the institutional framework legally separates issues of water resources management from water supply and irrigation, the Ministry of Water has a legal mandate for multi-sectoral coordination, and laws and policies governing water-intensive sectors encourage or require coordination with the water sector. Specifically, the powers given to the Minister of Water in Tanzania's Water Resources Management Act include, among others, the authority to "(b) appoint members of the National Water Board; (c) establish basin water boards; . . . [and] (e) facilitate sectoral coordination and coordinated planning on aspects that may impact on water resources . . . ," and the National Water Board, established under the act, advises the minister "on matters related to multi-sectoral coordination in integrated water resources planning and management . . ." (Government of Tanzania 2009). Implementation challenges remain, but the foundations are built into the legal and institutional framework and guide government stakeholders toward more inter-sectoral governance (World Bank 2017a). In Bangladesh, a multi-sectoral water platform has been formed that brings together government agencies, donors, and other partners to assist in the implementation of its multi-sectoral delta plan (figure 4.1). The platform provides a forum to coordinate fundraising, investment, and management around a multi-sectoral plan, while addressing cross-cutting issues like climate change and water stress.

FIGURE 4.1 Bangladesh Water Platform



Source: World Bank internal document.
Note: DP = Delta Plan; GP = Global Practice; IFC = International Finance Corporation; MFD = maximizing finance for development; PER = public expenditure review; PPP = public-private partnership; WRG = Water Resources Group.

Even with institutional enhancements to support multi-sector coordination, there often remain political challenges to successful functioning. Applied political economy analysis during integrated storage planning can help identify both the non-technical barriers to success and which policy measures and strategies will be most effective in unlocking technically preferred opportunities. It may be that the solutions identified will need to be adapted to fit prevailing realities, or there may be room to begin altering the relative influence of different stakeholders to create space for an improved approach (Fritz, Levy, and Ort 2014).

4.3 MULTI-STAKEHOLDER ENGAGEMENT AND COORDINATION

Early integration of multi-stakeholder (including non-government) perspectives and knowledge in water storage planning is beneficial and important, but it is not always hardwired into the regulatory and institutional framework. Water storage interventions, whether built or nature-based, have the potential to affect diverse stakeholder groups, in both positive and negative ways. In recent decades, there have been greater efforts to study and address the various environmental, social, and distributional impacts of water storage investments, especially for large built infrastructure; regulators that permit infrastructure developments increasingly have more rigorous standards around public consultation and disclosure. However, these regulatory requirements often come during the investment preparation phase where a preferred storage intervention has already been selected and has likely already secured funding to go forward. In the absence of earlier stakeholder engagement efforts, the potential for stakeholder opposition at this late stage is much higher.

Multi-stakeholder engagement is, thus, important from the earliest planning stages. This includes in the development of sectoral plans and basin-level/strategic studies, such as strategic environmental assessments (SEAs). As in the case of government agency coordination, ensuring the right composition of stakeholders from early on is also vitally important. In many instances, this would include non-governmental stakeholders like civil society organizations (CSOs), private industry, and local communities. In the case of indigenous and historically marginalized groups, securing their full and continuous engagement may require special effort, including through language interpretation and translation as well as working through the institutional structures of those groups. Still, this may be difficult to do in the early, public sector-led phases of water storage planning because of lack of funding or appropriate skillsets, especially in low- and middle-income countries.

The problem-driven, systems approach explicitly includes stakeholder considerations at various levels of the process. Early stages of the framework involve mapping of the various stakeholders that may be affected by a set of water storage options and whose behavior will influence the performance of those options. This early mapping is neither costly nor time-consuming and provides a foundation for later stages where more detailed information needs to be collected about stakeholder interests and capabilities. Having these considerations built in will help to screen out politically, environmentally, and socially infeasible options. By the time detailed stakeholder consultations need to be carried out for specific interventions that have advanced for further study, some potential issues will have already been identified and ideally fed back into the project concept.[3]

4.4 REGULATORY FRAMEWORKS

Many jurisdictions are missing or have outdated laws and regulations on water resources management and water storage. Existing laws and regulations may not reflect the actual level of water resources development or may not be detailed enough to manage the trade-offs that inevitably emerge with ambitious development plans. In addition to clarifying mandates and supporting multi-sectoral coordination, legal and regulatory frameworks will better facilitate integrated storage planning if they include protections for natural storage and areas that play a critical role in the provisioning of water.

Frameworks will support integrated planning if they emphasize the importance of basin-wide approaches, recognize the interdependence of built and natural systems, and include sustainable funding mechanisms for storage planning and management. For example, in Costa Rica, dedicated legislation (Law Nº 8023) was enacted in 2000 for the Upper Reventazón river basin, one of the most critical basins in the country for hydropower generation, for better management of the basin. Through this law, the Commission for the Planning and Management of the Upper Basin of the Reventazón River was established with a mandate for multi-sectoral coordination toward basin development and conservation (Porras Peñaranda 2012). The problem-driven, systems approach embeds these issues into the framework, so that if they are not explicitly provided for in the regulatory framework, they can still be considered in a systematic way. Some deficiencies in the regulatory framework may become apparent through the use of the planning framework and could be reflected in the regulatory reform process.

4.5 WEAK INSTITUTIONAL CAPACITY

Institutional clarity alone is not sufficient for integrated planning; responsible institutions must also possess the capabilities to carry out the mandates. As discussed, integrated water storage planning and operation require many parties to act. The operating environment is highly contextual; a given technology or approach that works in one situation is not guaranteed to work in another, however similar. This creates a heavy institutional burden for water managers. It can be difficult to build and retain the institutional capabilities needed for effective implementation, especially in countries that suffer from high rates of outward migration of their skilled professionals.

Long-term institutional strengthening is a critical aspect of integrated storage planning and operation. This includes the legal foundations that define the existence of relevant institutions, along with their roles and responsibilities and the obligations of other actors in the system. It also includes more detailed institutional arrangements, such as how different entities coordinate with one another, how they are staffed, and how they are funded. While legal and institutional frameworks are not static and must evolve over time to reflect the changing realities in a jurisdiction, it is much more effective and less costly to get the fundamentals right from early on. At this moment, many countries are going through a process of legal and institutional reform, especially as they introduce dedicated water management laws or policies for the first time or update their frameworks to reflect IWRM principles. This presents an opportunity to address the key elements that are needed for tackling water storage challenges through a problem-driven and systemic lens.

4.6 FUNDING CONSTRAINTS FOR WATER MANAGEMENT INSTITUTIONS

Financial sustainability of water management institutions is a well-documented challenge and a key barrier to holistic early planning of water storage interventions. Many water institutions suffer from chronic funding gaps driven by insufficient budget allocations from government, inadequate collections, or low tariffs that have been set below cost recovery for political or economic reasons. This can lead to understaffing, lack of data, and lack of resources to carry out sufficient early scoping, modeling work, and technical, social, and environmental due diligence. In low- and middle-income environments, studies that occur before the emergence of specific bankable projects are often funded by bilateral and multilateral partners or CSOs, often with grant funding. The extent to which resources are a challenge will be influenced by sectoral differences in revenue generating potential and the degree of private sector participation.

Lack of funding is also a problem for optimal management of existing water storage assets. This can lead to deferred maintenance of equipment and facilities, which not only affects their efficiency and quality of service delivery but also their safety. In a recent study of dam safety regulatory frameworks, which included case studies from 51 countries, only 14 percent of the case study countries were found to have a well-funded dam safety assurance program (Wishart et al. 2020).

Water management institutions are typically resourced by one of three basic sources: (a) tariffs or fees, (b) government budget allocations from tax revenue, or (c) transfers of monies or in-kind assistance from external sources such as development assistance. They may also have access to financing in the form of loans or bonds, which will ultimately be repaid to creditors using monies obtained through one of the three basic sources above.

The funding needs of institutions will vary according to their mandates, which may range from upstream planning and policy development, to project preparation and/or implementation, to asset management. Regulatory oversight might also be performed by agencies involved in sector planning or project development, or it may be the responsibility of an independent body. Depending on the functions, one or more of the basic funding sources could be more sustainable and appropriate, especially where independence is important.

4.7 PRIVATE SECTOR PARTICIPATION

Though this framework is fundamentally a public sector-led approach, it recognizes the important role of the private sector as a partner in integrated planning. Private sector participation in water storage planning and management can come in many different forms, from management and operation contracts, to purchase of previously public assets, to the provision of equity or loan financing. Private sector players may also have considerable expertise and access to technology that may be difficult to acquire in a fully public venture. Evidence from private sector participation around the world suggests that it may increase operational efficiency, leads to higher-quality service provision, and supports expansion of service delivery to underserved segments (Al-Madfaei n.d.).

However, the desire to attract private investment in water storage can lead to investments that maximize private benefits rather than net social benefits, resulting in slower progress in underlying development objectives. Private investors favor interventions that they perceive to be less complex, less risky, and faster to implement. In the case of hydropower, this has manifested as a preference for single-purpose run-of-river facilities, which have fewer stringent regulatory requirements in some jurisdictions (Venus et al. 2020). It has also manifested in a preference for smaller projects. According to the World Bank's Private Participation in Infrastructure database, 954 private investments in hydropower over the last century were for plants with installed capacity ranging from 0.4 MW to 11,565 MW, but 71 percent of those were for plants under 250 MW. Similarly, greenfield projects are preferable to brownfield projects. According to the same database, less than a quarter of private hydropower investments were brownfield investments, including for rehabilitation (World Bank 2022). While it is expected that private investors will prefer certain types of projects over others, if these preferences drive the selection process, it will limit the range of solutions and could lead to suboptimal choices.

Thus, during the early stakeholder mapping and analysis as well as later in the assessment of options against the agreed decision criteria, it is important to consider when and how it is most appropriate for private companies and investors to become involved in the project development process. It is also an opportunity for early thinking on what types of risk-sharing arrangements or incentives may be needed to crowd in private finance for the options under consideration, including nature-based solutions (NBS) for which investor confidence is generally lower. It is also important to consider what water rights—which may be closely tied to land tenure in some jurisdictions—are vested to private partners according to the various modalities of private sector participation and how those decisions may affect the water rights of other users in the basin.

4.8 MISALIGNED INCENTIVES AND POLITICAL ECONOMY CONSIDERATIONS

Where institutional arrangements are generally in keeping with international good practice, the political economy situation can lead to a mismatch between policy and implementation, making it harder to facilitate integrated storage planning and management. The specific non-technical drivers of this mismatch will vary from place to place, but they generally reflect a shift to institutional rules that challenge pre-existing norms and behaviors around water management. Integrated storage planning and management, and IWRM more generally, can be undermined, for example, by local political interference, privileged access of a select few, rent-seeking behavior, and power asymmetries between stakeholders. Problem-driven approaches account for such drivers of institutional non-performance by interrogating the underlying problems as well as different stakeholder interests and capabilities.

Among the issues common to infrastructure planning globally is the misalignment of political cycles and incentives with the timeframes needed to apply an integrated approach to storage development and operation. The path of least resistance is to implement what is already conceptualized, rather than taking a step back to undertake a wider planning effort. On top of this, electoral cycles typically last between two and six years, which is usually not enough time to take a water storage investment from the early scoping phase through to operationalization. For the largest and most complex engagements, it takes upward of a decade to bring them to fruition. While in office and seeking re-election, public officials are also under pressure to solve the most urgent crises and may opt for expedient, even if partial, solutions that can show results in the shortest time possible. Broadening the range of possible solutions by taking a problem-driven, systems approach to storage planning and management may yield some fast-to-implement solutions, but in most cases, the right combination of options to deliver sustainable and robust performance will include longer-term measures. Notwithstanding, water managers can leverage urgent crises like droughts and floods to spur action, including more resources for integrated planning. In addition, pragmatic approaches, such as implementing "no-regret" actions to show progress, may give more space to planners to undertake longer planning processes.

Implementing integrated storage planning will require some conceptual and attitudinal changes that will take time to be reflected in practice and in institutional frameworks for water management. Nevertheless, the problem-driven, systems approach can guide water managers through a step-by-step process that works around and through some of the institutional challenges. Table 4.1 summarizes some of the main areas where change is needed as well as some recommendations for how to manage them in the short term while longer-term solutions can be implemented in parallel.

TABLE 4.1 Changes Required and Recommendations for Integrated Storage Planning

WHERE WE NEED CHANGE	RECOMMENDATIONS
Hydrometeorological networks are insufficient	Earth observations can be a stopgap and are quickly becoming alternatives to in situ data collection
Complexity of water systems often yields highly technical and customized analytical tools that are expensive to maintain and require significant training	Free and low-cost analytical platforms are available and can be used to improve baseline understanding of existing systems and model possible changes
Unclear institutional mandates and outdated legal and regulatory frameworks make it difficult for agencies to coordinate integrated planning and development	Establishment of inter-agency platforms can support fundraising and multi-sectoral planning around cross-cutting issues and problems while institutional reform is in progress
Power asymmetries exist among different government ministries or other stakeholders; political interference of specific actors may undermine a rational decision-making process	Applied political economy analysis while planning water storage investments can help identify the non-technical barriers to success and find opportunities to advance technically preferred solutions
Multi-stakeholder engagements are not always hardwired into the institutional framework	Stakeholder mapping in the early phases of the investment planning helps to clarify stakeholder interests and capabilities and flag potential issues early
In funding-constrained environments, private investor preferences may drive project selection, yielding suboptimal investments from a socioeconomic perspective	It is important to recognize the private sector as a key player in storage development and management, but investor interests and capabilities should be mapped as with other stakeholders to detect where de-risking may be necessary to reduce mismatch between public and private interests
Politicians may be incentivized to implement politically expedient solutions even if they are not the technically preferred solution	"No-regret" actions can provide space to undertake a more informed planning process, and crises can be useful levers to generate support for technically preferred solutions

Source: Original to this publication.

ENDNOTES

1 Some of the high-resolution space-based global optical imagery records can be found here: The NASA/USGS Landsat Program, available at: https://landsat.gsfc.nasa.gov/; ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), available at: https://terra.nasa.gov/about/terra-instruments/aster; SPOT, available at: https://earth.esa.int/eogateway/missions/spot; Ikonos, available at: https://gisgeography.com/ikonos-satellite/; QuickBird Satellite, available at: https://earth.esa.int/eogateway/catalog/quickbird-full-archive.

2 More resources about geospatial information can be found in https://www.spatialagent.org/HydroInformatics/ and more information on World Bank Global Reach Spatial Agent Portal for Water: http://www.appsolutelydigital.com/GlobalReach/map.html.

3 For further resources, see Dye, Hulme, and FutureDAMS-Consortium n.d.

5 TOOLS FOR BETTER STORAGE THROUGHOUT THE PROJECT CYCLE

Integrated water storage management does not end at the planning phase outlined in chapter 3. Closing the water storage gap sustainably and efficiently requires a life-cycle approach to managing storage assets from planning, investment preparation, and implementation, through to operation, and in some instances, eventual decommissioning (figure 5.1). This chapter draws from guides and tools that have been developed on the technical, environmental, social, and institutional good practices in water storage development and management. While it cannot give full treatment to the breadth of relevant issues, it highlights some specific areas that are important to consider from a system perspective for both new and existing storage assets.

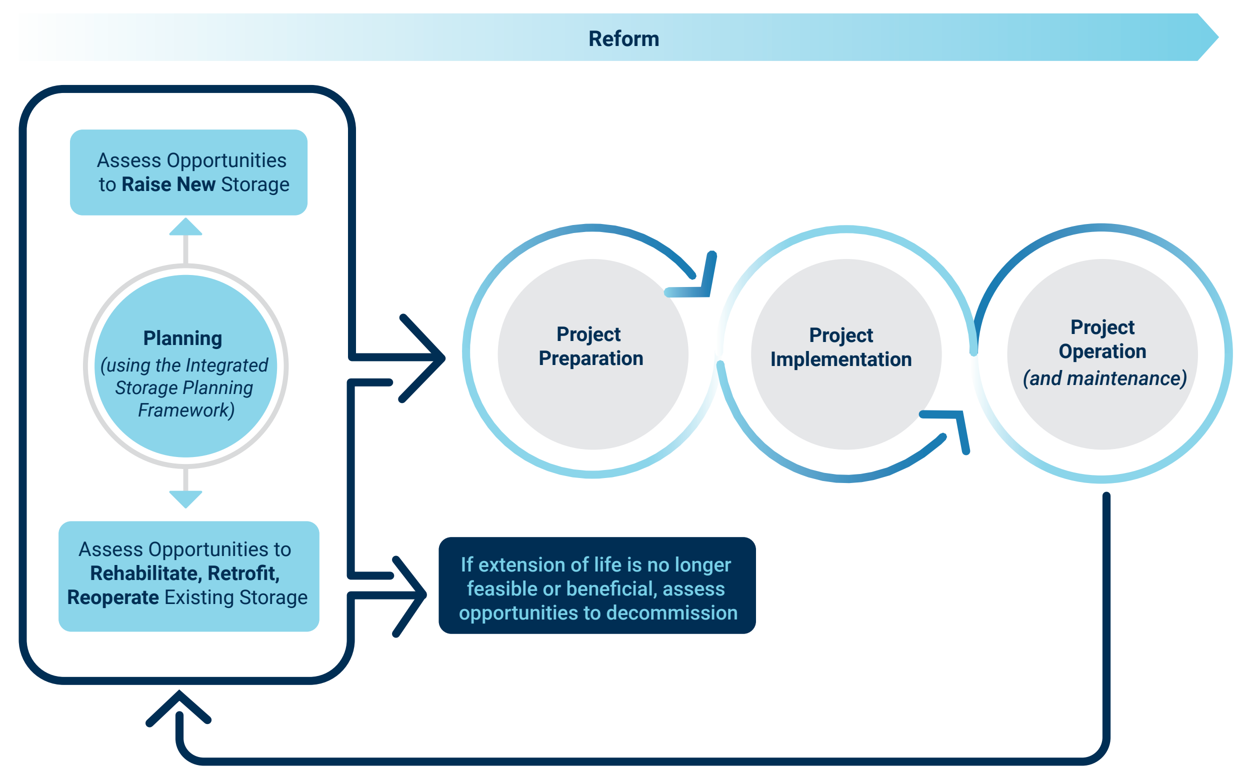
5.1 RAISING OR CREATING NEW STORAGE

After the initial planning phase, specific water storage investments, whether natural or built, need to be prepared in more detail and then implemented. For new investments, this usually involves more steps than investments involving existing storage assets.

5.1.1 Preparatory Studies for New Investments

More detailed investigations are needed to examine the feasibility of the potential investments prioritized via the options assessment process. Feasibility studies, defined broadly, investigate the technical, financial, economic,

FIGURE 5.1 The 5 R's and the Project Cycle



Source: Original figure for this publication.

environmental, social, and governance aspects of a proposed investment. They are important for understanding the various trade-offs involved in developing or, in the case of nature-based solutions (NBS), tapping into water stores to support water service delivery, accelerate the clean energy transition, and strengthen resilience to climate change and natural variability. Linked environmental and social impact assessments (ESIAs) scope potential impacts and look at mitigation options, informed by the mitigation hierarchy. Specific measures can be explored as needed, including the establishment of environmental flows. Capitalizing on opportunities for greening of areas surrounding reservoirs can also enhance the aesthetic and ecological value of artificial reservoirs, creating habitats for biodiversity and attracting eco-tourism.

There are many types of assessments that can be useful for assessing and minimizing impacts of potential water storage projects. At the project level, project ESIAs and environmental and social management plans (ESMPs) are focused on the potential positive and adverse impacts of the specific project and are usually required as part of the project permitting process by national or subnational authorities. Though normally required, they do not have to be solely compliance-oriented; on the contrary, they can be useful tools for building local acceptance of a project and identifying opportunities where said project can go beyond the satisfaction of legal requirements. Within these tools, the Mitigation Hierarchy provides guidance on designing projects to avoid risks and impacts, to minimize or reduce residual risk, to mitigate remaining impact, and compensate where necessary. See box 5.1 for an overview of environmental and social tools. Refer to World Bank Environmental and Social Standards (ESS) 1 on Assessment and Management of Environmental and Social Risks and Impacts for specific World Bank requirements.

The Mitigation Hierarchy (ESS 1: Assessment and Management of Environmental and Social Risks and Impacts)

- Anticipate and avoid risks and impacts
- Where avoidance is not possible, minimize or reduce risks and impacts to acceptable levels
- Once risks and impacts have been minimized or reduced, mitigate; and
- Where significant residual impacts remain, compensate for or offset them, where technically and financially feasible.

At the investment preparation stage, assessing the sustainability of a specific storage project will be easier if strategic/basin-level analyses are completed. If a strategic environmental assessment (SEA) or cumulative impact assessment (CIA) has been carried out, many environmental, social, and governance risks and opportunities will already have been scoped and provide important input into the project-specific environmental and social impact assessments and management plans. Project ESIAs and ESMPs can be tools for building local acceptance and identifying opportunities to exceed legal requirements. For example, community benefit sharing is considered good international industry practice for storage investments since the communities bearing most of the cost of the project, such as livelihood disruption or physical relocation, may not be the same communities that are the direct beneficiaries of the investment. Thus, it is important for both equity and social acceptability of the project that the local communities directly share in the benefits.

Depending on the nature of the storage facilities being investigated, there may be a need to revisit the needs of the system. This ensures continued alignment between the different options being considered, both at the project level as well as in larger system planning, in addition to ensuring that resources are not wasted along the way. Depending on the nature of the potential investments, there may be a need for more detailed study of the system, through SEA (if not already done during the options assessment) and/or CIA. Re-examining the needs of the system is also a way to achieve greater operational linkages among different water storage types that may be operating in isolation.

For instance, **many governments hold master plans or other planning documents that are decades old, and the status quo in the basin may be drastically different from when new dam projects were first identified and assessed.** In this case, a CIA may prove a useful tool to evaluate the cumulative impacts of the interventions across the basin to determine whether the proposed intervention will provide adequate benefits to offset costs of the intervention and consider how to minimize those costs. In the case of

BOX 5.1 Types of Impact Assessments to Maximize Social and Environmental Development

Strategic environmental assessments (SEAs),[a] also called strategic environmental and social assessments, are defined by the World Bank's Environmental and Social Framework (ESF) as a systematic examination of environmental and social risks, impacts, and issues associated with a policy, plan, or program, typically at the national level but also in smaller areas or in a specific sector. SEAs are typically not location specific; rather, they are prepared in conjunction with project and site-specific studies that assess project risks and impacts (World Bank 2016b). For water storage, an SEA is likely to be applicable to (or part of) a water storage master plan or a river basin management plan that incorporates water storage. Because SEAs are applied at an early stage, they have meaningful input on key choices in the design of the water storage system. They serve to facilitate multi-stakeholder decision-making at a high level. SEAs are increasingly required by national regulators and financiers as part of the ESIA process.

Alternative assessments, also known as option assessments, identify alternatives to a planned project that achieve the same goal while generating higher environmental and social benefits. They should be an integral part of any impact assessment study, but in some cases they can be used as a stand-alone analysis. Alternative assessments look at a system from a cross-disciplinary perspective and, as such, are especially suitable to support the decision process related to water storage development by bringing environmental, social, and economic considerations into early decision-making. A serious analysis of alternatives can also reduce the project cost, assist in gaining greater public support for the project, and improve the likelihood of project approval by the various stakeholders. In most instances, if this opportunity is not acted upon, the best that can be achieved is damage limitation during project implementation (ADB 2012).

Cumulative impact assessments (CIAs) are done to determine the summative impacts of past, present, and reasonably foreseeable future developments on valued ecosystem components (VECs). VECs can range from wildlife population to ecosystem services and social development. A CIA can be an integral part of an impact assessment study or can be a stand-alone study. CIAs are frequently used to assess the impacts of multiple hydropower developments within one river network. In this case, the VECs identified will mostly be associated with the river network that the hydropower projects have in common, such as endemic or endangered species, types of habitats, or cultural heritage. When looking at water storage in a broader perspective, CIAs can be used to assess the impacts of multiple water storage projects (e.g., simultaneous implementation of multipurpose dams, rural water storage, and managed aquifer recharge) in one basin. CIAs are increasingly required by national regulators and financiers as part of the ESIA process.

Environmental flow assessments (EFAs) provide information on how the physical characteristics of a river could change with planned developments, how ecosystem services and biodiversity could be impacted, and how all these changes could affect people and local and wider economies. There are many different methods (IFC 2018) to determine environmental flows, which range from using hydrological and hydraulic data to determine a minimum flow in a river to holistic methodologies addressing the condition of the whole river ecosystem. To be most effective, EFAs should also be an integral part of a wider body of environmental planning and assessment tools, such as an SEA, CIA, or EIA.

Biodiversity assessments analyze specific risks and impacts of projects on biodiversity and natural habitats, including through the identification of the types of habitats, species, and ecosystem services potentially affected and consideration of potential risks to and impacts on the ecological function of the habitats, especially those ecosystems that have protected status (national, local, international). Also analyzed is whether the project will pose threats to species that are of significant local interest for livelihoods or nutrition or are of global or national conservation interest (endangered, Red List, etc.) (World Bank 2018a). Following the assessment, a biodiversity management plan may need to be prepared.

[a] For more information, see World Bank 2013.

(box continues next page)

BOX 5.1 Types of Impact Assessments to Maximize Social and Environmental Development (cont.)

Project-specific environmental and social impact assessments (ESIAs) are done to determine the potential positive and adverse impacts of a specific project and are frequently required by national legislation or international financiers. An ESIA is often carried out in parallel with the (pre-) feasibility stage of project design and follows a few distinct steps: screening, scoping, baseline study, impact assessment, and mitigation and enhancement measures. Many ESIAs also include an alternative assessment, but as this is carried out at a stage where most of the strategic decisions on project design (technology used, location) are already taken, this alternative assessment usually takes the form of a description of earlier high-level considerations or focusses on lower-level alternative considerations that can still be influenced. ESIAs are an essential tool to incorporate opportunities for social and environmental enhancement in the project design and are important in building local acceptance and ownership of projects.

ESMPs also known as Environmental and Social Management and Monitoring Plans, are the outcome of an ESIA process and provide an overview of all mitigation and enhancement measures that have been identified, who is responsible for the implementation, information on their costs and planning, and who is responsible for monitoring the implementation and effect of the mitigation and enhancement measures. The ESMP is an essential document in which required follow-up of the environmental and social process for a project is made specific.

Environmental and social audits are an instrument to determine the actual impacts of existing projects or activities and to what extent mitigation and enhancement measures are effective and adhered. The outcomes of an environmental and social audit may lead to changes in the ESMP or the project as a whole.

the Poonch River in the Upper Indus River Basin, the government in collaboration with the International Union for the Conservation of Nature (IUCN) carried out an SEA in the wider Mahaseer National Park, and subsequently conducted a CIA and EFA of a specific hydropower project to determine the best way to meet development objectives across sectors, including hydropower, fisheries, and the environment. It also provided information for an EFA to determine the water requirements to maintain downstream ecosystems. The methodology employed for those studies provides a useful model for others in similar situations. (See Jhelem-Poonch River Basin case study, chapter 8.)

Sustainability audits are useful in verifying the sustainability performance of a potential storage project and helping to identify gaps to be addressed before proceeding. In the case of hydropower, the Hydropower Sustainability Tools, produced by the Hydropower Sustainability Council, offer a comprehensive assessment of project sustainability at different stages of the project cycle, including preparation. They include more than 20 topics, including project-affected people, biodiversity, environmental flow regimes, Indigenous people, climate change mitigation, and overall systems for managing environmental, social, and governance issues.[1] Though the tools are hydropower-specific, many of the issues are relevant to other projects related to dams, and the organizing framework is relevant to other technologies as well (Lyon 2020).

5.1.2 Greenhouse Gas Emissions and Climate Resilience

Given the climate crisis, due diligence of storage investments—large ones, especially—should also include evaluation of the project's expected greenhouse gas (GHG) footprint. Rivers are major conveyors of carbon from terrestrial areas to lakes and the sea; terrestrial areas are generally net carbon sinks, and aquatic systems are net carbon emitters (World Bank 2017b). The construction of a dam and impoundment of a reservoir alters the GHG cycle, resulting in a change in flux of GHGs to the atmosphere compared with the situation before the reservoir was created. Some of the GHGs will be displaced from one part of the river system to another, while additional GHGs could be released depending on the availability of carbon and characteristics of the air and water (Liden

2017). Research on GHG emissions from reservoirs is a relatively new scientific activity, and most studies have been conducted during the last 25 years. However, tools have been developed to estimate the potential GHG emissions from a planned dam based on a range of environmental and design factors (IHA 2017). Depending on the services the project is being developed to deliver, a dam that is a net emitter of GHGs may still turn out to be a climate change mitigation project, depending on the counterfactual situation.

Storage projects may provide opportunities to store GHG. For example, as mentioned previously, altering operation of existing reservoirs or using a wetting/drying method in paddy fields can reduce methane emission. In addition, as the largest terrestrial carbon pool, soils have a key role to play in climate change mitigation. Soil carbon comprises 9 percent of the mitigation potential of forests, 72 percent for wetlands, and 47 percent for agriculture and grasslands (Bossio et al. 2020). Sustainable soil management practices could increase soil carbon and overall soil health while reducing soil carbon losses by promoting reduction of soil disturbance, maintaining or regenerating soil cover, and maximizing plant and soil biodiversity. Similarly, forest management (e.g., land preservation, reduced harvest) can contribute to climate change mitigation by promoting forest carbon sequestration. Water storage projects that include these activities, such as those including sediment management to prevent erosion, watershed/landscape management practices to promote NBS or sustainable agriculture practices, such as climate-smart agriculture, could generate climate benefits, in addition to financial, environmental, and social benefits.

Given the uncertainty of hydrological flows because of climate change, it is important to also evaluate whether investments are robust and can withstand a range of climate futures. There exist few tools to inform investment decisions that include an assessment of the climate risks faced by water resources management projects. Past hydrology may not be an accurate reflection of future hydrology because of climate change. Downscaling of climate projections from time series of general circulation models (GCM) may also not be accurate, because of (a) their irreducibility to scales relevant to water resource projects, for example, GCM models are unable to accurately predict local hydrological variability and extremes, and (b) the relative magnitude of the impacts of climate change on the project, as compared to other variables, such as population growth, technology, and demand, that remain difficult to estimate and mitigate. As such, it is necessary to employ tools like the Decision Tree Framework (DTF) in box 5.2.

5.1.3 Dam Safety During Investment Preparation and Implementation

For dam projects, the management of safety risks begins in the investigation and design stage. A dam needs to be designed by experienced and competent professionals, and certain safety measures should be included in the design. The International Commission on Large Dams ICOLD (2005) says, "*the traditional approach to dams engineering is that in which risks are controlled by following established conservative rules as to design events and loads, structural capacity, safety coefficients and defensive design measures*." Based on preliminary assessment, new dams should be classified based on size and/or potential hazard. This will inform the design criteria, including the inflow design flood and the maximum earthquake for which the dam should be designed. For large dams and dams that could cause safety risks, irrespective of size, it is good international industry practice (and a requirement for World Bank financing under ESS4) to establish an independent panel of experts. A panel of experts provides review from as early as the investigation phase and through detailed design, construction, and the start of operations (World Bank 2020). The articulation of dam safety plans is also a critical aspect of securing a new dam for the communities downstream. Dam safety plans that should be assembled during project preparation are (a) a construction supervision and quality assurance plan; (b) an instrumentation plan; (c) an outline for the eventual operation and maintenance plan; and (d) a framework emergency preparedness plan (World Bank 2020).

As in the design phase, experienced and competent professionals are needed during dam construction. According to ICOLD, 50 percent of dam failures occur during construction, first impoundment, or the first five years of operation (ICOLD n.d.). Dam safety measures for the implementation period should be built into the bid tendering process with a detailed and clear scope of work. Depending on the complexity and risk involved, it may be necessary to pre-qualify bidders to ensure that only those with proven expertise can be selected. Review by

BOX 5.2 Confronting Climate Uncertainty in Water Resources Planning and Project Design

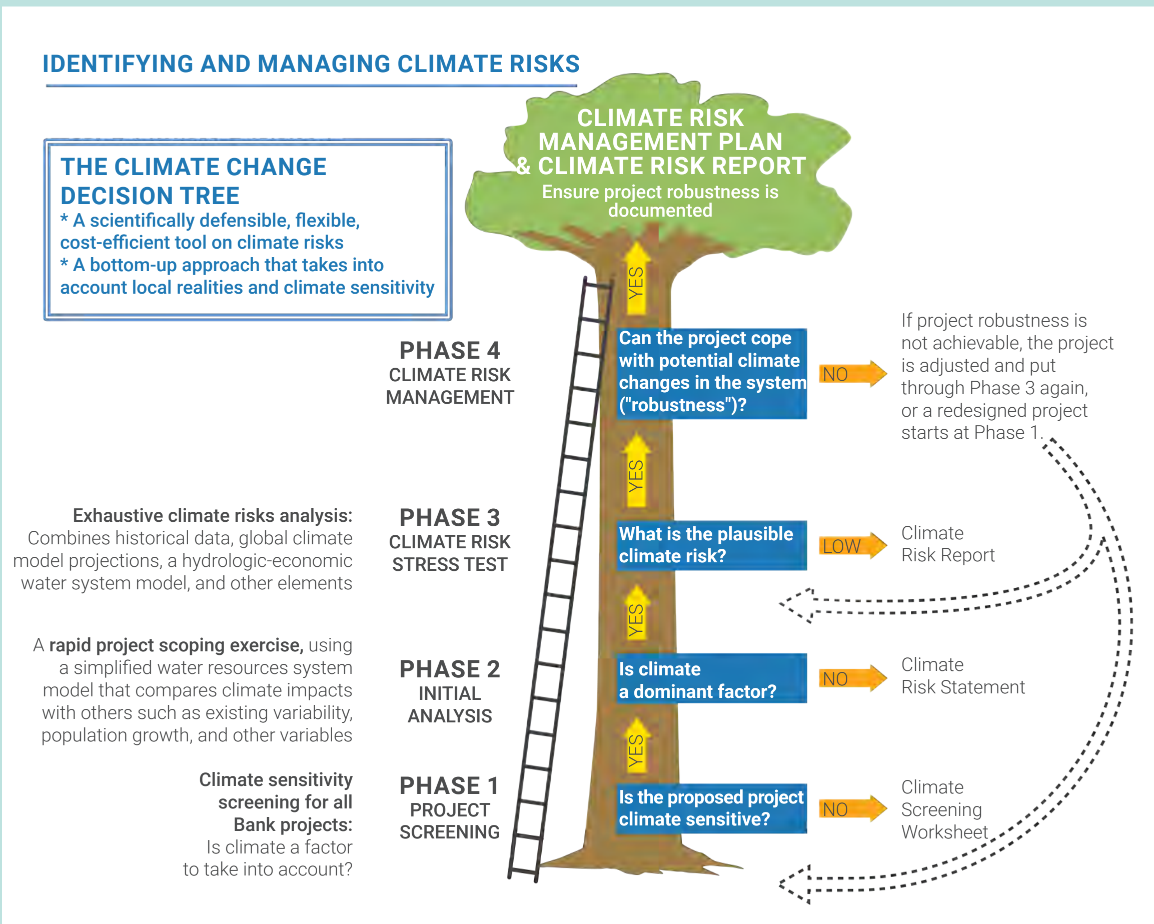
Approach

How do you know if a new potential storage project is resilient to climate change?

In 2015, the World Bank introduced a Decision Tree Framework (DTF) to help identify and manage climate risks in water resources projects (figure B5.2.1). It takes into consideration local realities and sensitivities and builds bottom-up through a four-phase hierarchical process to prepare a Climate Risk Management Plan and Climate Risk Report for the project under evaluation.

In the first phase, Project Screening, the decision-maker explores climate sensitivities in context of the four C's: choices, consequences, connections, and uncertainties. In phase 2, Initial Analysis, a rapid project scoping exercise is conducted using a simplified water resources system model that compares climate impacts with existing variability, population growth, and other variables to see if climate is a dominant factor. Phase 3, Climate Stress Test, combines historical data, global climate model projections, a hydrologic-economic water system model, and other elements to determine the plausible climate risk. And finally, in Phase 4, the decision-maker tests for robustness—returning to phase 3 if adjustments can ensure robustness, or to phase 1 if there is a need to redesign the process.

FIGURE B5.2.1 Decision Tree Framework Phases



Source: Ray and Brown 2015.

(box continues next page)

BOX 5.2 **Confronting Climate Uncertainty in Water Resources Planning and Project Design (cont.)**

For projects exiting the decision tree at Phase 3, cost-benefit analyses must include safety margins and sensitivity analyses, given that these projects were identified in Phase 2 as having significant potential sensitivities to climate change, though current climate change projections do not indicate a high likelihood of resulting system failure (relative to performance threshold). Four descriptors that might be used to characterize the robustness of a project in Phase 4 are (a) climate sensitive, that is, whether its performance is affected by climate at all; (b) reliable over a wide range of climate risks, that is, though it might be sensitive to climate change, its performance thresholds might not be violated; (c) vulnerable to very costly failures, that is, though it might resist failure, if it does fail, it might fail catastrophically; and (d) resilient, that is, able to recover quickly from failure to previous levels of performance.

The DTF provides a scientifically defensible, flexible, cost-efficient tool for assessing climate risks. In the Chancay-Lambayeque watershed in Peru, the DTF was applied to assess the robustness and resiliency of the system to climate risks and inform prioritization of infrastructure interventions to address inadequate water supply, flood risk, and environmental degradation.

Good Practices

When evaluating risks faced by a proposed water project, it is important to include climate risks alongside economic, political, and other natural risks. When evaluating the relative importance of climate and non-climate factors, one might consider initial water stress conditions, recent local climate and demographic trends, and length of project life.

One must use outputs from all available GCMs to ensure that the largest available subset of possible climate futures is applied.

Stakeholder consultation is fundamental to the bottom-up approach and must be used for characterizing historical system performance, desired future performance thresholds, and vulnerabilities to change.

an independent panel of experts throughout the procurement and construction process of complex and high-risk projects offers significant value as members can suggest cost-saving design alternatives and identify project risks from an early stage. Preparation of dam safety plans for the construction period is critical. Monitoring against the construction supervision and quality assurance plan and implementation of other dam safety plans are also crucial, as is the selection and use of the right construction materials to ensure the dam's structural integrity under design stresses.

Critical conditions during construction that require careful analysis include the flood discharge that will be adopted for the temporary river diversion. The recurrence period of such flood may be adopted rather low in order to limit the capacity as well as the cost of a diversion. When a diversion tunnel needs to be constructed, its cost can be considerable. Most likely the period of diverting the river discharges will be selected to coincide with a dry season, and any delay in construction progress of a dam closing section may threaten timely completion as well as the quality of the dam. Completing a closing section of a dam in a hurry because of time pressure may lead to compromised construction and be a safety risk. The dam safety panel and authorities responsible for supervision should carefully review the proposed method of execution and make sure that the contractor has a viable plan B in case of a delay or another accident.

Another critical point will be the time of first filling of a reservoir. Often that will be allowed to commence when a dam body has reached a certain elevation. The pace of raising the reservoir level often should not exceed a certain prescribed speed. However, in case of an extreme inflow, the pace of raising could be higher and require immediate release of the excess inflow. In that case, a flood release structure with sufficient capacity should be operational. Another period with higher risk occurs during and just after first filling of the reservoir when the underground and the dam abutments are being saturated. During this period the performance of the dam should be carefully monitored visually and by piezometers and surface beacons, and any leakage discharges should be recorded in order to be able to make decisions on how to proceed in case of unexpected behavior. The stage of first filling is a period in which the occurrence of dam breaches is higher than in other periods.

5.1.4 Early Consideration of Sediment Management

Planning for sediment management must begin during project conceptualization. Traditionally, dam reservoirs and other forms of storage have been treated as an exhaustible resource, constructed for use over a predicted design life calculated based on sedimentation rate and trap efficiency. At the end of this life, the infrastructure is decommissioned. This attaches with it certain issues of generational equity (with costs borne by future generations), which are heavily discounted in the initial economic analysis. Decommissioning also creates a need for new reservoirs—a costly and inefficient cycle. Instead, proper planning for sediment management can ensure that the lifetime of a storage option is properly estimated and can realistically be attained. Box 5.3 provides further information on the life-cycle approach to sediment management in storage planning.

5.1.5 Funding for Storage Investments

Funding can be a critical constraint to storage development. Especially for large investments with high capital

BOX 5.3 A Life-Cycle Approach to Sediment Management

Approach

A life-cycle approach to infrastructure planning means reservoir storage is actively planned to perform as a renewable resource and sustained through the incorporation of sediment management technologies from the beginning of the project. The World Bank first introduced the life-cycle approach in the reservoir conservation approach, or RESCON model, in 2003 to identify technically and economically optimized reservoir sediment management strategies. The Bank has since upgraded the approach and added further guidance on practices for hydro and water supply projects.

Sediment management integrates one or more of the following three options: (a) reducing sediment yield from upstream, typically using reforestation and construction of sediment retention structures, (b) sediment routing (managing flows during high yield to minimize trapping), typically through sluicing, bypassing, and density current venting, and (c) redistribution from active to dead storage zones or removal of deposits through flushing, hydraulic, or mechanical dredging. In addition to using these methods to manage sediments at headworks, in a run-of-river project one must consider removal of sands from water diverted for power generation. Common challenges relate to flow imbalances, hydraulic short-circuiting, and excessive hydraulic loading.

An example is the Dasu Hydropower Project, a 4,320-MW run-of-river facility to be constructed on the Indus River. To preserve reservoir volume and protect hydraulic machinery, the project is designed to be equipped with outlets and flushing tunnels that can jointly be used to discharge 4,400 cubic meters of water per second to remove deposited sediment (Annandale, Morris, and Karki 2016).

Finally, adaptive strategies can be taken up where, instead of handling deposited sediments, storage volumes and equipment are modified. Examples include raising dam walls, applying protective coatings on equipment, and providing sacrificial civil structures.

(box continues next page)

BOX 5.3 A Life-Cycle Approach to Sediment Management (cont.)

When choosing between options, one must consider technical as well as economic feasibility. Consider for example the case of hydrologically large reservoirs holding 0.5 times mean annual inflows. Flushing and dredging become unfeasible both from a cost and technical effectiveness perspective. Monitoring and management must therefore commence as early as possible, and sediment inflows restricted to the extent possible. Planning considerations must include hydrologic data, suspended sediment data, long-term sediment yield and variability calculations, hazards posed by extreme events, sedimentation modeling, and a careful consideration of upstream and downstream impacts.

Resources: Annandale, Morris, and Karki 2016; Palmieri et al. 2003; HydroSediNet: https://www.hydrosedi.net/
Hydropower Sediment Management Knowledge Hub: https://www.hydropower.org/sediment-management

outlays, loan or additional equity financing may be needed to supplement internal budgets of the entity developing the project. Funding may come from private and/or public sources, including development assistance in the form of loans or grants. Because of their revenue-generating potential, some types of storage projects may be more likely to obtain private repayable financing; other investments, because of their development importance and contribution to other related development goals, may be higher priority for limited government-backed funding through budget allocations or earmarked sources. Large, transformational storage projects also need "patient" financing (long-term financing, with a grace period and low interest rates) as the risks owing to technical uncertainties are highest at the start of the project and diminish with time.

Storage assets, such as hydropower facilities or facilities supporting agricultural production, have benefit streams that can be monetized to secure the loan or equity financing that is needed for their development. Water stored in hydropower reservoirs, for example, generates revenues tied to electricity tariffs, which tend to better reflect the real cost and value of energy services compared to water tariffs, which are typically well below the real value, and sometimes the cost of providing water. Reservoir and pumped storage hydropower facilities generate ancillary services, including voltage and frequency control, for the electrical grid that can be monetized; while markets for ancillary services are underdeveloped, this function of reservoirs for energy storage is increasingly recognized and being remunerated (IEA 2021). Privately funded hydropower schemes also have long-term off-taker arrangements that provide for the sale of power to a single buyer or a small number of buyers. This independent power producer model has few parallels in bulk water supply and none for other water storage services like flood protection.

Publicly financed storage projects can more easily be developed to meet development goals. When governments are the primary or only shareholder of a storage project, they can exercise a greater degree of control over how those facilities are designed and operated, including whether to design them as multipurpose facilities and which sectors are prioritized for use. They also have more control over the tariffs that will be paid for the services provided by those facilities (Plummer Braeckman, Markkanen, and Souvannaseng 2020), which may be influenced by factors other than cost recovery and profit maximization, such as affordability and impacts on poverty reduction goals. In some sectors, like hydropower, fully publicly funded projects are, however, becoming less common. Since 2000, fewer hydropower projects in low- and middle-income countries were funded exclusively from public sources. China is the exception. Projects there have been developed largely with public sector money, much of it provided by domestic development banks (Plummer Braeckman, Markkanen, and Souvannaseng 2020).

In low- and middle-income countries, public funding for water storage investments often involves development assistance. This may come either from development banks such as the World Bank or regional banks like the Asian, African, and Inter-American Development Banks, or from bilateral aid agencies. For hydropower, development financing institutions have provided most of the public investment, which for the period 2013 to 2017, amounted to more than $37 billion on average each year (IRENA and CPI 2020). From fiscal years 2000 to 2017, the World Bank committed over $8 billion in financing for hydropower projects, which is more than one-third of the financing it provided for all renewable energy technologies during that period (IEG 2020). Projects supported by multilateral development banks are reputed to take longer, but there is limited evidence on how those delays compare to public-private partnership (PPP) projects, and some research points to delays being more closely related to country context (Plummer Braeckman, Markkanen, and Souvannaseng 2020). Climate financing, much of which is administered through development financing institutions, is another source of funding for storage projects, but the amounts committed have been relatively limited. Funding for mitigation projects far exceeds the funding available for adaptation from climate funds. In terms of water storage, hydropower projects, which can generate certified emission reduction credits (carbon credits), have received some limited mitigation financing ($693 million between 2003 and 2018), while adaptation funding for water storage has been focused on small-scale interventions such as water harvesting, small-irrigation, micro-dams, and landscape-related investments (CFU database 2022).

Private involvement in storage investments can take many forms. There are several different models of private sector participation when it comes to storage projects, ranging from fully private endeavors by private utilities or captive projects developed by industry for their own use, to PPPs with varying degrees of private interest and control. For larger, centralized storage projects with higher capital costs, private sector actors may be involved as equity partners; in such cases, there might be split ownership of facilities or the creation of special purpose vehicles with multiple shareholders, including public and private investors. Private operators can be brought in for publicly owned facilities through a concession agreement or an operation and maintenance contract after commissioning. Alternatively, a PPP can be extended through construction and operations by way of build-operate-transfer or build-own-operate-transfer arrangements, where private partners source their own financing for project construction and retain control (and in some cases ownership) of the asset for some time before handing it over to the government. To reduce the risks of such investments and attract private partners to the table, multilateral institutions can offer partial risk guarantees and political risk insurance. These PPP arrangements are more common for hydropower facilities, though they exist in other subsectors, such as municipal water supply. There are few examples, if any, of PPPs in a classic sense in smaller, distributed water storage or for nature-based storage, but there are many examples of non-government interest and funding arising from community or civil society sources. Further, the pricing of ancillary services provided by hydropower, including for ramp-up of production for grid stability—a form of reliability that has opened the possibility for more cost recovery—is providing greater incentive for private sector financing of hydropower. While a relatively new concept, the exploration of pricing of ancillary services of storage to increase reliability beyond hydropower in other water sectors, may yield better cost recovery from reservoirs (IEA 2021).

Financing innovative NBS with few immediate/directly monetizable benefits through traditional means can pose an impediment to their adoption, but in recent years, investment has been increasing. In 2015, an estimated $25 billion was invested in nature-based infrastructure for water worldwide and increased annually by more than 11 percent between 2013 and 2015 (Bennett and Ruef 2016). Historically, there have not been many specific financing mechanisms for investment in NBS (Davis, Krüger, and Hinzmann 2015). In the water sector, these investments have been dominated by government-subsidized efforts at the local scale (WWAP 2018), concessional financing, and grants allocated by governments, which may be motivated by potential social and environmental co-benefits, private finance pursuing opportunities for green investing, and development finance incentivized to maximize resilience, sustainability, and poverty reduction. For example, in Monterrey, Mexico, where urbanization on the floodplain of the San Juan River Basin has left it susceptible to both floods and droughts, stakeholders have worked together to develop the Monterrey Metropolitan Area Water Fund. This fund, which aims primarily to reduce the impacts of floods and maintain safe access to affordable drinking water, focuses on the rehabilitation of the watershed to improve green storage capacity. This has been done through reforestation and land and soil conservation in areas of the watershed that produce 60 percent of Monterrey's water supply. See the case study in chapter 8 for more information.

Other sources of private finance are emerging for both NBS and built storage options that meet high environmental, social, and governance standards. Green bonds and other sources of green financing are on the rise and have the potential to mobilize much more financing for sustainable water storage projects. The demand for green bonds actually outstrips the ability of green bond issuers to identify and validate eligible projects (OECD 2022). This fast-growing asset class has increased the amount and diversity of financing options available to water storage projects (box 5.4).

5.1.6 Implementation of Storage Solutions

Any water storage project involving construction of new infrastructure must fulfill the requirements of techno-economic viability, environmental safeguards, and social acceptability. Detailed project reports are prepared according to the guidelines and standards, which need to be progressively revisited to account for technological advancements, new issues, and safety concerns. Reports of impact assessments on environment and social aspects are expected to give a complete picture of the overall positive tangible and intangible effects due to the project. The guidelines issued by environmental protection agencies or the concerned ministries for impact analysis generally refer to the impacts of development projects during the life cycle of the project, positive and adverse, and mitigation/compensation measures, in addition to monitoring activities to implement corrective measures. Construction of projects might involve temporary structures, which also need to be safe and minimize their disruption on natural systems. Also, special consideration should be given to the interaction of the new project with the existing environment and infrastructure base. For instance, in the case of cascade systems, the impacts of the project on existing facilities should be examined.

Along with population growth and higher awareness of environmental damage from construction of water storage projects, more stringent laws and procedures for protection of environment and ecology have been enacted in recent decades. In addition to feasibility studies, environmental impact assessments have been made for the guidance of state agencies. Necessary safeguards are an essential part of decision-making and evaluation

BOX 5.4 Green Financing

Problem

Financing available through traditional public sources, such as tariffs, taxes, and transfers, are often insufficient to finance infrastructure owing to tight public budgets and low tariffs driven by affordability and political constraints. Against this backdrop, financing innovative nature-based solutions with few immediate/directly monetizable benefits through traditional means can pose an impediment to their adoption. Alternative financing opportunities exist in the form of concessional financing and grants allocated by governments motivated by potential social and environmental co-benefits, private finance pursuing opportunities for green investing, and development finance incentivized to maximize resilience, sustainability, and poverty reduction.

Approach

Instruments used for leveraging private sector funds for green financing include:

Water funds: Downstream water users, including private sector companies, agricultural producers, and hydropower plant managers, may join forces with upstream communities, water utilities, and conservation nongovernmental organizations (NGOs), to create water trust funds for investing in catchment restoration upstream. This is a type of payment for ecosystem services (PES). In many cases, a multi-stakeholder governance board monitors project impacts and selects/identifies new investment opportunities. This model is seen in the Greater Cape Town Region, where catchment restoration through the elimination of invasive plants was assessed to deliver greatest gains in water supply at the lowest unit cost. Highly replicable, there are 24 such water funds known in Latin America and two in Africa.

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BOX 5.4 Green Financing (cont.)

Green bonds: Issued to raise funds for investments that generate environmental or climate co-benefits alongside a financial return. Proceeds from the bond issue are used for eligible investments defined upfront together with evaluation and selection criteria for such investments. They help finance green infrastructure by spreading the costs of the project over its useful life in the form of periodic fixed income payments. An example is the 2017 issuance of £250 million Green Bonds by Anglian Water Pvt. Ltd. for 60 green projects, including construction of wetlands in the river Ingol watershed with the potential to generate £10.4 million in cost savings related to water treatment, as well as 53 percent water consumption savings, 89 percent reduction in CO_2 emissions (lower energy use and lower levels of dissolved organic carbon), adaptation benefits (flood risk reduction), and biodiversity co-benefits.

Environmental impact bonds: Impact bonds use proceeds for a particular green investment and links payouts to the performance of the investment in order to share risk with investors who are encouraged by the model to conduct own due-diligence and may earn reputational benefits from investing in these projects. A golden example is the 30-year, tax-exempt $25 million bond issued by DC Water to two private investors, for financing installations to reduce stormwater runoff and thereby reduce dumping of combined sewer overflow into its rivers, thereby protecting the city's watershed and ecosystem. Similar models are now being replicated in cities around the United States.

Other instruments: Include tax increment financing, business improvement districts, stormwater retention, and credit trading, stormwater purchase agreements, insurance payments for risk reduction, corporate stewardship to protect own source waters, and traditional public-private partnerships (PPPs).

On the public side, there are general transfers, earmarking of revenue, dedicated service fees, issuance of municipal bonds, and environmental mitigation/compensation funds into which payments must be made for causing unavoidable impacts on ecosystems. Meanwhile development finance institutions can contribute through direct lending or pay-for-success financing models.

Climate Finance

Water storage projects can generate payments for emission reductions or increases in carbon sequestration. Restoration of forests, through afforestation or reforestation, peatland, and wetland restoration, in addition to agricultural practices that promote sustainable soil management, could generate carbon benefits. Such emission reductions or enhanced carbon storage may allow land managers to leverage finance from entities in the private sector, civil society, multilateral funders, or buyers in the carbon market seeking to offset emission, as well as potentially contributing to Nationally Determined Contributions (NDCs) and other existing measurement, reporting, and verification (MRV) frameworks (World Bank 2021c).

The Ethiopia Humbo Assisted Natural Regeneration project is an example of tapping into climate financing instruments to improve land degradation, in addition to other environmental and economic benefits. Supported by the World Bank's BioCarbon Fund, the project has taken a community-based approach to land restoration in the Humbo region, a drought-prone area where around 85 percent of the population live in poverty (Donaldson 2009). Poverty, hunger, and increasing demand for agricultural land have driven local communities to over-exploit forest resources, which threatens groundwater reserves that people depend on for potable water. Soil erosion is also a severe problem in the Humbo region, which is exacerbated by heavy rain events. Among the results and achievements of the project (World Bank 2015), in less than four years, the project has restored 2,700 hectares of previously degraded land in Ethiopia and boosted crop yields. The project's community-based approach has made a lasting environmental impact and generated emission reductions that provide revenue that is invested back into local communities (e.g., carbon payments are made to the community to invest in grain mills, storage, and community infrastructure).

(box continues next page)

BOX 5.4 **Green Financing (cont.)**

Good Practices

In situations where affordability and/or collectability of revenue streams associated with benefits of green storage are low, and long-term-income guarantees are absent, such as urban sponges for flood management, public instruments and concessional funding must be used to leverage private funds.

Countries must develop policies and institutional and regulatory frameworks to support the leveraging of private finance for green investments. Measures can include tax incentive programs, performance-based subsidies or conditional transfers, promoting market-based approaches, clarifying risk-sharing mechanisms for PPPs, and setting up dedicated offices for guiding and planning investments.

Resources: Browder et al. 2019; Dougherty, Hammer, and Valderrama 2016; and Wishart et al. 2021.
The Nature Conservancy. Water Funds Toolbox. Accessed March 10, 2022. Available at: https://waterfundstoolbox.org/project-cycle
Donaldson, K. 2009. *Humbo Community Managed Forestry Project, Ethiopia.* Climate Change, Community Forestry and Development, Climate Change Case Studies, World Vision Australia, Farmer Managed Natural Regeneration (FMNR). Accessed March 10, 2022. Available at: http://fmnrhub.com.water storage.

processes, and in almost all countries, new projects are now subjected to environmental impact assessments (ICID 2004). Any assessment needs to be generated according to the legislative framework applicable to the project. In some cases, there is a law on environmental assessments that provides for the procedure and matters related to environmental assessment of projects in which the government is involved either directly in implementation or indirectly by providing approval or permission for implementation. Other policies to consider are those potentially covering water resources, environmental protection, prevention and control of water pollution, forest conservation, and resettlement and compensation measures, among others.

The implementation of water storage solutions requires an inclusive approach across all sectors and all government levels. National agencies provide leadership in the definition of the water storage solutions being implemented, but considering the multifaceted nature of these solutions, cross-sectoral collaboration is necessary to ensure sound optimization of outcomes across the country's development objectives. In addition, the decisions and actions of society will determine the ultimate effectiveness of government efforts. Water storage projects need to equally prioritize technical expertise with social engagement through dedicated programs to promote stakeholder participation, social inclusion, communication, education, research, and ensuring public access to information throughout the project life cycle. Involving communities in the implementation of small-scale storage and NBS is important, particularly for those solutions that require their action to ensure sustainability and maintenance during operation.

5.2 OPERATING AND MAINTAINING EXISTING STORAGE

Beyond the planning phase, utilizing best practices in operating and maintaining water storage can not only extend the life of water storage assets, but make them operate more efficiently as well. Each storage type, whether built or natural, is connected through the larger hydrological system and, thus, should be managed as such. For example, operational rules of built storage should consider ecological flow regimes in the wet and dry seasons. Monitoring the water resource, in addition to the storage type, is also important, so that adjustments can be made to storage operations to adapt for changing hydrological conditions. In terms of maintenance, the needs of natural and built infrastructure may look very different, but maintenance is critical for optimal operation, extending the life of the storage type and ensuring its safety. Water storage facilities that are properly maintained can deliver services for decades without the need for major refurbishment; in contrast, facilities that are improperly operated and neglect routine maintenance will be prone to defects and will frequently need to be refurbished. In the worst cases, poorly operated and maintained storage assets may undermine their very objective and even become the danger themselves; this is especially true for reservoirs that have become filled with sediment and offer little to no flood control for the communities that have settled downstream of them.

It is good international practice to begin preparation of an operation and maintenance strategy during the feasibility stage of water storage project preparation. Early consideration of how a facility will be operated and maintained can have many benefits, including improving investor confidence. It may also influence the final design of major components. A well-developed operation and maintenance strategy will include (a) a diagnosis of the asset fleet and operational environment; (b) objectives with key performance indicators; (c) a set of activities and plan for their implementation; (d) contractual arrangements; (e) a human resources plan; and (f) cost estimates and funding plan (World Bank 2020b).

Operation and maintenance of water storage includes preventative and corrective maintenance that is necessary for the smooth functioning of the assets and to detect inefficiencies and defects that might lead to a failure. Operation and maintenance of water storage assets includes regular safety inspections, assessing the condition of assets, purchase and installation of spare parts, repairs, and monitoring of instrumentation. In many instances, routine maintenance is delayed due to budget constraints. It cannot always be avoided, but deferred maintenance can accelerate deterioration and increase the costs of corrective measures.

For dams and reservoirs, a life cycle or sustainable use approach to sediment management can be applied both to new and old projects. In the case of old projects, this means modifying initial operations configurations to improve the balance between sediment in- and out-flows, while continuing to generate significant benefits. In the face of significantly reduced storage volumes, hydropower projects may be forced to transition to run-of-river or power peaking operations with operational and structural modifications. This option is unavailable to reservoirs meant for water supply, irrigation, and other consumptive uses. Monitoring is critical to sediment management and must include periodic bathymetric surveys, analysis of sediment cores, and characterization of suspended sediment concentration and particle size distribution in water delivered to turbines and outlet works.

Continued monitoring and adaptation of outcomes to meet environmental flow targets are also needed. Operational rules will need to be implemented to maintain the agreed ecological flow across days or seasons. Additional changes may be needed to meet water quality targets, for example (Linnansaari et al. 2012; Williams et al. 2019).

Dam safety is also a critical consideration in operation and maintenance. Currently, there are more than 58,000 large dams registered with ICOLD with several million smaller dams estimated to exist globally. Dam failures are rare events, but the consequences of failure can be significant, with major failures resulting in loss of life and damage to infrastructure, communities, and the ecosystems located downstream. While dams are generally becoming safer thanks to improvements in design, construction methods, and surveillance, other factors have led to increased risk associated with dams, including changing hydroclimatic variables from climate change and shifting settlement patterns with more people moving into the areas downstream of dams. The global stock of dams is also aging, which is increasing the needs for major maintenance and refurbishment. About a third of the current stock of large dams have been operating for 50 years or more (Wishart et al. 2020). For hydropower, nearly half of global capacity is more than 30 years old (Morgado et al. 2020). It is extremely important to ensure that dams are structurally sound and have essential dam safety management measures in place due to the fact that so many people and economic sectors depend on dams functioning safely (Ueda, Pons, and Lyon 2021). See box 5.5 on risk-informed dam safety management in India and the case study on dam safety in Indonesia (chapter 8) for further details.

5.3 REOPERATING, RETROFITTING, AND REHABILITATING EXISTING ASSETS

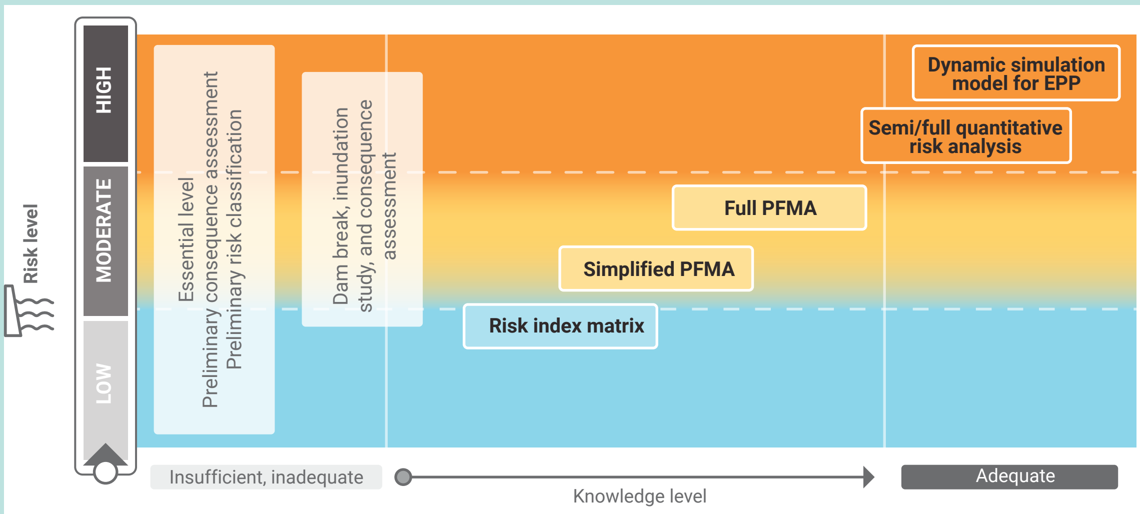
5.3.1 Reoperating

Large gains in water storage services, such as enhanced flood mitigation, improved hydropower generation, or

BOX 5.5 Risk-Informed Dam Safety Management

Increasingly, risk-informed approaches to dam safety are being employed due to recognition that some dam safety incidents caused by non-structural issues may not be well-captured by the traditional standards-based approach. Risk-informed approaches can range from relatively simple qualitative analysis to rigorous, quantitative methodologies based on the probability of failure (figure B5.5.1). These approaches require more institutional capacity, but they can lead to more efficient allocation of financial resources and prioritization of measures and monitoring activities.

FIGURE B5.5.1 Risk Analysis Tools for Dam Safety



Source: World Bank 2020a.
Note: EPP = emergency preparedness plan; PFMA = potential failure mode analysis.

For countries or companies with a large portfolio of dams, portfolio risk assessment techniques that can provide a comparative estimation of risks overall are being used with more frequency. The Risk Index Method is a basic, qualitative portfolio risk assessment tool, relying mostly on visual inspection of dams, that enables screening across a portfolio of existing dams using color-coded risk matrices or additive scoring methods to characterize the likelihood of failure. It is not a measure of risk based on the estimation of failure probability for individual dams but provides a relative indication of potential risk within the portfolio and, as such, is helpful for evaluating and prioritizing safety issues in a systematic way. Several countries have developed risk index (or similar) tools, including Australia, Canada, the Czech Republic, New Zealand, Poland, the Republic of Korea, and South Africa. In India, the Central Water Commission (CWC) is developing a risk index scheme, which it intends to apply to over 5,000 large dams. Under CWC's Risk Index, risk is defined as the product of fragility of the dam and the potential hazard associated with the dam with fragility scored according to three subcategories: (a) technical characteristics of the dam; (b) existing conditions of the dam; and (c) safety plan for dam safety (table B5.5.1).

Good Practices

Portfolio risk assessment, using risk indexing, can be supplemented by more advanced risk assessment methods for higher risk dams. Some critical failure modes could be missed or underestimated because risk indexing approaches largely rely on visual inspection of the condition of dams (World Bank 2021e). Refer to the Technical Note on Portfolio Risk Assessment Using Risk Index (World Bank 2021b) for methods of developing a risk index considering potential failure modes of dams.

(box continues next page)

BOX 5.5 Risk-Informed Dam Safety Management (cont.)

TABLE B5.5.1 Fragility Categories and Factors for Central Water Commission's Risk Index Scheme

TECHNICAL CHARACTERISTICS		EXISTING CONDITIONS		SAFETY PLAN	
1	Dam age	1	Seismic design	1	Design documentation
2	Inflow design flood	2	Installed flow control equipment	2	Operation and maintenance manual
3	Seismic zone	3	Flow control equipment condition	3	Emergency preparedness plan
4	Landslide, glacier lake outburst flow, landslide dam outburst flow, debris flow	4	Presence of backup power	4	Organization, staff number, capacity, qualification
5	Length	5	Access to site	5	Safety inspection, monitoring, and reporting
6	Conduits	6	System operation	6	Dam safety reports, analysis, and interpretation
7	Filters	7	Concrete gravity structure	7	Follow-up actions
8	Foundation and abutments	8	Spillway structure		
		9	Masonry structure		
		10	Embankment, foundation, and abutments		

Source: World Bank 2020a.

A first step in portfolio risk assessment is establishing the portfolio. In India, the World Bank supported development of a web-based system for dam-related asset inventory and management under the first Dam Rehabilitation and Improvement Project (DRIP I, 2010–2021) by bringing together stakeholders across the federal government. The system now contains a basic inventory of 5,000 large dams and comprehensive records for about 1,485. Several thousand small dams are not included in the inventory at present. It will be further developed under the DRIP II project to include automatic monitoring, data acquisition, and operational systems.

Resources: Wishart et al. 2020; World Bank 2020a, 2021b.

the minimization of water loss from evaporation, can come from reoperating current water storage. Dam operating rules are often determined at the time of dam design and are often not updated to reflect changing water availability and patterns of water use downstream. In other cases, dams may be designed to provide a range of services (from hydropower to irrigation to flood control) but, for various technical and non-technical reasons, are only ever operated to meet the demands of the primary service. There are many examples of large gains obtained through the reoperation of existing systems. Decision support systems (DSS)[2] have been widely used to better inform dam operators how to make decisions on releases in a systematic way that balance coexisting water uses and protection of the ecology. Some DSS are generally supported by a hydrodynamic model and can include forecast of flows and of climate as well as optimization for cascade systems. Such is the case of the multipurpose Tres Marias dam in the São Francisco River, in the Brazilian state of Minas Gerais, which provides hydropower generation, flood control, navigation, municipal and industrial water supply, and irrigation. It is one of several large multipurpose reservoirs located in the São Francisco River and its tributaries. An operational forecasting and

DSS were developed that integrate different sources of ground information, remote sensing data, and numerical weather predictions with hydrological and hydrodynamic models to generate short-term flow forecasts for up to 15 days ahead for each of the reservoirs (Miltenburg n.d.).

Given advancements in inflow forecasting, it is possible to increase the value of services provided by dams through the employment of forecast-informed reservoir operation (FIRO). By altering reservoir levels based on short- or long-term forecasts (to increase storage capacity in advance of a flood event or to conserve storage if a dry spell is predicted), additional storage services can be delivered through better deployment of existing infrastructure. The FIRO case study provides a methodology to assess the feasibility of and to pilot FIRO in two reservoirs in California (see case study, chapter 8). Good hydrometeorological monitoring capability is an essential ingredient for implementing FIRO; increasingly, machine-learning assisted tools are proving effective for probabilistic forecasting, using both in situ and satellite-based observations.

Reoperating dams can provide drought relief in the short term, in dire situations of water shortage. From 2015–18, the City of Cape Town experienced a 1-in-590-year drought, and water storage was critical to managing water supplies during it. In addition to demand management measures, short-term water exchanges or transfers (e.g., from agriculture to urban use) proved important. Cape Town arranged a transfer of water from a group of irrigators in an area that had a surplus. In order to be able to manage storage in this fashion, clear water allocation mechanisms and policies were necessary. The Cape Town experience illustrated that water allocations (and associated water rights) from the integrated system need to be regularly updated to ensure that these rights fall within the available yield for a given assurance of supply. In the absence of this, the system will be less secure and the impacts of droughts more severe.

5.3.2 Retrofitting

Retrofitting existing storage can provide new services without building an entirely new project. Retrofitting refers to the addition or expansion of the production capabilities of an existing water storage facility, including electric power generation or water supply services or flood control.[3] According to ICOLD, fewer than 20 percent of the world's large dams are used for hydroelectric generation (Yuguda et al. 2020), offering an opportunity to consider retrofitting those dams to enhance their capabilities. In the United States alone, there are more than 50,000 suitable non-power dams with the technical potential to add about 12 GW (31 TWh/year) of hydropower capacity through retrofitting (United States Department of Energy 2018). Compared to the construction of a new dam, and under certain conditions, retrofitting can provide a cost-effective way to increase and enhance/optimize water production. Impact on the environment can be less severe as most substantial impacts have already been caused through the initial project construction (Energypedia 2015). With around 30 percent of dams worldwide being multipurpose (OECD 2017) and increasing demand for storage services in some areas, it is crucial for policy makers to comprehend and plan for growing trade-offs between key functions by allowing provision for multipurpose use in law and policy, as well as through developing capacity for such multi-sector work to occur.

Retrofitting involves different options and can serve different purposes. To meet base or peak electricity demands, reservoirs that are already in existence for other purposes can be fitted with hydropower generators (Yuguda et al. 2020). Existing non-power dams can be retrofitted for hydropower generation without the costs and impacts of additional dam construction. Similarly, existing hydropower dams may be retrofitted with more efficient variable-speed turbines and higher capacity generating equipment. Retrofitting can also be used to facilitate sediment sluicing (Sumi et al. 2015) and improve sediment management (Kondolf et al. 2014), modifying dams to accommodate probable maximum flood (Graham 2000), earthquake retrofitting to improve reliability and safety, and returning the reservoir to its original storage capacity (Santa Clara Valley Water District 2021). Operators can have more operating flexibility, which can be translated into potential cost savings, if facility equipment is retrofitted to adjust to changing operating conditions. Instrumentation retrofitting could also be used for continuous monitoring and inspection of dams to identify timely rehabilitation and for dam safety purposes (Melih Yanmaz and Ari 2011). As mentioned above for reoperations, hydrometeorological monitoring and forecasting data is critical; without this information, reservoir operation is less flexible and may not be able to capture the potential benefits of increased water supply, hydropower generation, and flood control.

Retrofitting with floating solar panels, or incorporation of solar panels into facets of storage facilities such as irrigation channels, can create synergies with the electrical sector by reducing investment in electrical grid infrastructure or by providing electric supply for onsite consumption. Many reservoirs, especially those of hydropower plants, have nearby grid connections to which the floating solar panels could connect. Usually, dry seasons with less water flow correspond to periods of high solar potential and vice versa. Combining the two technologies in some areas can reduce seasonal variations in power production. Also, a hybrid system can optimize the diurnal cycle by leveraging more solar power during the day and hydropower at night. In the case of large irrigation reservoirs, water treatment plants, cooling ponds for industrial use, or other energy-intensive infrastructure, the onsite self-consumption of the electricity produced by the installed floating solar panel could further decrease costs and energy losses. This offers great potential worldwide for the combined and integrated operation of dams and floating solar panels (World Bank Group, ESMAP, and SERIS 2019).

Even though retrofitting can be an attractive alternative to building greenfield storage projects, some financial barriers remain. Inexistent, unclear policies and regulations about retrofitting that translate into lengthy permitting and licensing process, prolonged development timelines from inception to operation, lack of investor knowledge, and other project development risks are just some financial barriers for retrofitting projects (Patel, Shakya, and Rai 2020). In addition, investors remain hesitant to finance non-power dam electrification projects due to a lack of financial standards or analysis on their project valuation and economics, a lengthy and complex regulatory process that leads to project uncertainty, and minimal state and federal support to stimulate development and financing (Guerrero 2021). Another concern is related to schemes of revenue allocation and who will benefit, in addition to the priority setting for water allocation (Energypedia 2015). Also, it is harder to make the case for rehabilitating and retrofitting existing hydropower plants to access climate financing (Patel, Shakya, and Rai 2020).

However, private finance mobilization for retrofits is possible, and there are examples of policy reforms to promote retrofit and rehabilitation. One example of private financing is the Pamir Private Power Project, aimed at retrofitting and rehabilitating hydropower plants and associated infrastructure in the Gorno Badakshan Autonomous Oblast region, Tajikistan. Pamir Energy Company was formed through a PPP with the Government of Tajikistan acting as regulator, and the Aga Khan Fund for Economic Development, a private NGO, which has a controlling 70 percent share of the company. The International Finance Corporation (IFC, whose debt was converted into equity in 2007) has a 30 percent share. Pamir Energy Company has a 25-year concession agreement, allowing a long-term approach and flexibility with respect to returns. Through WB-IDA and IFC financing and a Swiss grant for subsidies for poor consumers, the power supply in the region improved from only around 3 hours per day to around 24 hours of power supply per day in winter to customers of the main grid (over 70 percent of the total customers) (Jumaev n.d.). Experiences like this one can be promoted or further expanded through adequate policy reforms. In the United States, the recent Twenty-First Century Dams Act intends to incentivize retrofitting, in addition to rehabilitation and decommissioning of dams, while conserving waterways to build stronger, more resilient water infrastructure and hydropower systems in the United States (Landers 2021).

5.3.3 Rehabilitating

If not adequately maintained, water storage infrastructure may fall into disrepair and need rehabilitation to function effectively; even if well-maintained, equipment wears out after a period of time and needs to be replaced. Through development or even misuse, natural ecosystems may lose their storage capacity as land is denuded, soils are depleted, and floodplains are built over. Rehabilitation of the storage alone may not be sufficient to fill a water storage deficit, but when compared with the cost of new infrastructure, the restoration of existing assets and getting them fully operational again may be the lowest cost option for increasing water storage availability in a system. One example is Sri Lanka, where ancient tanks are being rehabilitated to provide water for irrigation, household use, industry, and the environment. The case of tank cascade rehabilitation in Sri Lanka illustrates the importance of evaluating rehabilitation of small-scale water storage at the level of a sub-basin tank cascade, providing examples of a methodology that can be used to evaluate the value of linked small-scale storage, as well as a process to prioritize investments in storage rehabilitation. Further, the case study on dam safety in Indonesia provides examples of how dams were assessed and prioritized for rehabilitation.

Finally, natural ecosystems can be rehabilitated, and natural storage capacity restored, as is the case in Monterrey, Mexico (see case studies, chapter 8).

5.4 DECOMMISSIONING BUILT STORAGE

Even if the decommissioning of water storage is the last stage of its lifespan, it remains important to use good practices through this phase. When it is decided that water storage will no longer be rehabilitated, reoperated, or retrofitted to extend its lifetime, it should be decommissioned (box 5.6). This is often not simply a task of stopping utilizing the storage but taking into consideration what impacts decommissioning could have on stakeholders, including social and environmental considerations. In the case of dam decommissioning, if the dam has altered the ecological status of the river through changing the flow regime, and the ecosystem has been altered and has adjusted around these changes; an assessment may be needed to understand how a decommissioning could help—or harm—the downstream system. Aspects to consider in decommissioning include distribution of benefits and costs across owners and other stakeholders and the related ways to finance the decommissioning, public safety, fish passage, river restoration, sediment management, and other environmental impacts (USSD 2015). At this stage, the Mitigation Hierarchy may again be a useful tool. Several references exist to help dam owners and stakeholders investigate and evaluate the possibility of dam decommissioning, including those from the United States Society on Dams and the Government of Australia.

BOX 5.6 Dam Removal: A Tale of Too Much Storage?

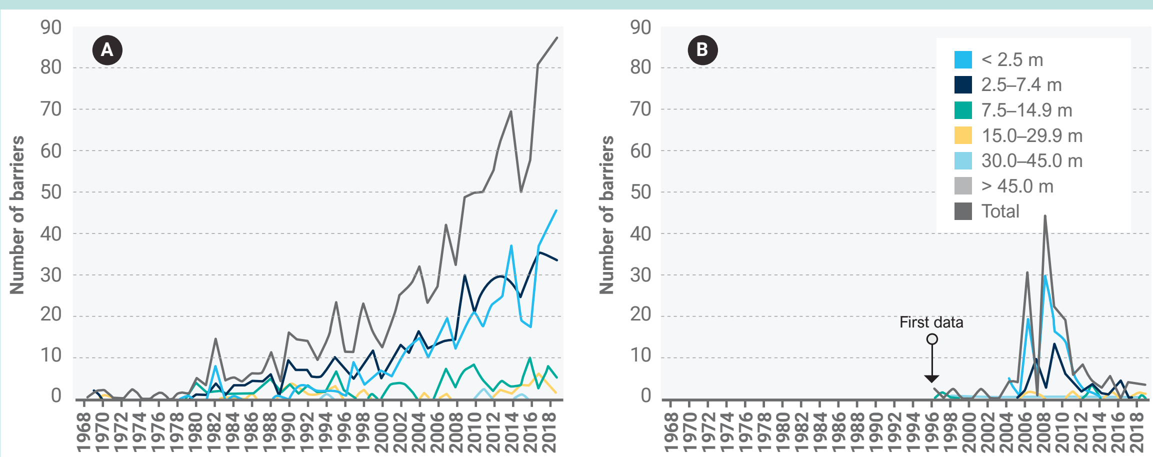
What Is Dam Decommissioning?

ICOLD defines *dam decommissioning* (or dam removal) as ranging from *a partial breach of the dam to full removal of the dam and appurtenant facilities* (ICOLD 2018). The United States Society on Dams uses the term *retirement* to refer to the discontinued use of a dam (USSD 2015).

Trends in Dam Removal

In the United States, an estimated 1,654 dams were removed between 1968 and 2019, and thousands more could be removed by 2050 (figure B5.6.1). Of the dams removed, 99 percent were below 15 meters in height. Since the 1980s, an

FIGURE B5.6.1 Number of Dams Removed on the Rivers of the United States and Europe



Source: Habel et al. 2020.
Note: Number of dams removed in the United States (panel A) and Europe (panel B). Data for Europe exclude Sweden, Russia, Wales, and Scotland.

(box continues next page)

BOX 5.6 Dam Removal: A Tale of Too Much Storage? (cont.)

increasing trend is observable with the number of dams removed growing each decade. In Europe, some 342 dams were removed between 1996 and 2019, and as in the United States, the vast majority—98 percent—were low-height dams (Habel et al. 2020). Globally, some 3,869 dams are estimated to have been removed over the last half century, with dam removal starting to gain momentum in the Republic of Korea and Japan (Ding et al. 2019).

Most of the dams being removed are older dams. In the United States, 78 percent of dams that have been removed were built before 1940, with dams built as far back as 1750 included (Habel et al. 2020). Research shows a clear upward trend in the median age of dams that have been removed (Ding et al. 2019).

Drivers of Dam Removal

A public debate around the issue of dam decommissioning was launched by a report by the United Nations University Institute for Water, Environment and Health (UNU-INWEH) in 2021, which discussed the risks posed by a "mass ageing" of dams and removal as an option to address the emerging threat of obsolescence (Perera et al. 2021). The aging of the world's fleet of dams is, indeed, a concern due to rising maintenance costs, sedimentation, loss of efficiency, and others, as noted in the UNU-INWEH study (Perera et al. 2021), though statistics on dam failures suggest the highest probability of dam failure is in the early years of a dam's life (ICOLD n.d.). Based on evidence assembled to date, safety concerns do factor into decisions around dam removal, including both public safety and concerns around high-hazard dams or dams with structural deficiencies. Overall, the reasons behind the increase in dam decommissioning and removal are complex and varied, including not just safety-related considerations but environmental, cultural, economic, and legal as well.

In the United Kingdom, safety is considered the primary reason for dam removal, with many dams located near to densely populated areas, and this is also a major factor in the United States for small dams as more than 280 public safety incidents related to persons crossing small or low-head dams have been recorded between 2000 and 2015 (Habel et al. 2020).

Ecological restoration, which is closely linked to changing values around the environment, is also a major driver of dam removal. In the United States, dam removal is concentrated in Western states and northern Midwestern states (Bellmore et al. 2017), with some of the most famous examples relating to the restoration of salmon habitat. The Glines Canyon and Elwha dams, for example, were simultaneously removed from the Elwha River in Washington State between 2011 and 2014—the largest dam removal project to date in the United States (NOAA n.d.). Dam removal in Europe is closely related to the implementation of the Water Framework Directive in 2006, compliance with which is driving river restoration projects in France, Spain, Sweden, and other countries in the European Union (Habel et al. 2020). Similarly, in China, which has the largest number of dams of any country, its vision of shifting to an "ecological civilization" and restoring degraded rivers may lead to future removal of smaller, aging, and low-efficiency dams (Liu, Zhou, and Winn 2020).

Another driver is regulatory change. It is said that "standards age faster than dams." Across the world, changes to environmental and safety regulations related to dams have led many dams, particularly small and privately owned dams, to fall out of compliance. It is, sometimes, more costly to rehabilitate or reoperate the infrastructure to meet new standards than to decommission. In the State of Massachusetts, for example, a cost comparison of alternatives for three dams that did not meet state regulations concluded that removal was on average 60 percent less expensive than repair and maintenance over 30 years (IEc 2015). Dam owners may opt to decommission their dams rather than be saddled with the potential legal liabilities of having non-compliant dams, in addition to the costs of repairs.

(box continues next page)

BOX 5.6 **Dam Removal: A Tale of Too Much Storage? (cont.)**

Notwithstanding these considerations, decommissioning of dams can be controversial as the future benefits of well-maintained infrastructure need to be weighed against the benefits of removal, which implicitly involve societal and cultural values around water.

Lessons

After multiple extension-of-life investments, some dams will eventually need to be decommissioned or removed due to various reasons. Even though decommissioning may be less costly than alternatives, the up-front costs of removal are still a barrier and are usually not accounted for during project development and operation.

Changing societal values influence decisions around dam removal directly as well as through updated environmental and safety regulations. Multi-stakeholder engagement in the planning phase helps ensure that selected investments are more societally acceptable, and selecting investments that are robust to a range of different future scenarios may result in infrastructure that is more adaptable in the long run.

ENDNOTES

1 http://hydrosustainability.org.

2 Any tool that facilitates decision-making processes and supports more rational decisions.

3 In this study, the definition of retrofitting includes upgrade, which can consider a project in which existing generation capacity is augmented and is more encompassing than those definitions of retrofitting found in some literature that refer only to the construction of generation facilities at non-hydropower dams.

6 THE FUTURE IS NOW: A CALL TO ACTION

The ***Call to Action*** summarizes the key conclusions and recommendations of this report around four themes:

1. **Why** focus on water storage?
2. **What** do stakeholders need to understand to develop smarter approaches?
3. **Who** needs to be involved?
4. **How** can stakeholders approach storage more strategically?

6.1 WHY FOCUS ON WATER STORAGE?

Water is fundamental to life. It's at the center of economic and social development and influences whether communities are healthy places to live, farmers can grow food, or cities have reliable clean energy. Water underpins natural ecosystems, drives industry, and creates jobs. It touches every aspect of development, with a direct link to almost every Sustainable Development Goal (SDG).

Water insecurity is growing around the world, influenced in some places by increasing demand, in others by degrading quality, and almost everywhere by climate change. Addressing water security is much broader than water storage, but water storage is a key part of building water security, particularly to manage the increasing variability and growing extremes being brought about by climate change. Climate change means that even countries with relatively temperate climates and large infrastructure endowments face increasing water insecurity, such as in Europe at the time this report is being published. For much of the world, "business as usual" is not a viable strategy.

Smarter approaches to water storage will, inevitably, lie at the heart of responses to climate change. Water storage provides three broad services: (a) improving the availability of water during drier periods, (b) mitigating the impacts of floods, and (c) regulating flows for other purposes, such as hydropower, transportation, or recreation. Storage not only provides these direct services but is also a form of hydrological risk management: families, farmers, businesses, and cities will invest more in their lives and livelihoods when they feel protected from water extremes.

As water storage grows in importance, current methods for developing and managing it are more obviously inadequate. Total volumes of freshwater storage have declined over the last 50 years, some large infrastructure solutions have proved far less resilient—and far more damaging—than had been initially understood, and many approaches in general have been too fragmented and short term to add up to the more comprehensive, sustainable, and integrated solutions that circumstances increasingly demand.

The result is that the world today faces growing demand for water, increasing variability, and a growing water storage gap—and current approaches to filling the storage gap—are no longer fit for purpose.

> ***Call to Action Step 1:*** *Focus more—and more strategically—on water storage.*

6.2 WHAT DO STAKEHOLDERS NEED TO UNDERSTAND TO DEVELOP SMARTER APPROACHES?

Freshwater storage takes place in a wide array of forms: built and natural; large and small; underground and on the surface. While humans have been developing water storage systems for several millennia, nature has always provided the vast majority of freshwater storage on which humans depend—whether knowingly or not. The first thing necessary to know, therefore, is what storage is already being utilized, particularly the natural systems such as groundwater, wetlands, glaciers, and soil moisture reserves. Systematic mapping of natural and built storage on a basin-by-basin basis (as this is the practical operating scale of most storage systems) is needed, including data about volumes, reliability, and controllability of the water stored. Understanding current storage systems is the first step toward not taking storage for granted and unnecessarily depleting it, as many parts of the world have been doing for several decades. It is also a necessity for informing future planning and investment decisions.

The second knowledge challenge is to understand storage as a system. Even very different types of storage are linked as part of a broader water cycle, meaning that they generally need to be developed and managed as an integrated system rather than as stand-alone facilities. Engineers have long understood that dams depend on their watersheds, but it is time to go much beyond this and understand not only the hydrological system but also the broader social, economic, and environmental systems that interact with it, building upon decades of global experience with integrated water resources management (IWRM). The social and economic systems are drivers of changing demand for storage services, while the broader environmental systems (biological, climatic, etc.) are both major users and shapers of water flows.

The third key knowledge challenge is assessing potential alternatives to storage. Storage challenges usually need to be addressed as part of a broader water resource context, and storage may not be the best solution to the problem at hand. Alternatives to storage could range from demand management to alternative supply measures for reducing scarcity; from zoning regulations to flood insurance for managing floods; and from alternative energy to alternative transport investments to storage's regulatory services. The important point is to consider alternative ways to deliver the service, not simply volumes of water.

The fourth big knowledge challenge is to develop and manage storage within a context of increasing uncertainty brought about by climate change. Managing storage as a system is a key step in the right direction since a diverse system will be more resilient to weather-related shocks than individual facilities. The fact that the past is no longer a reliable guide to the future has several ramifications, including a premium on the rapid collection and analysis of data to guide system understanding and management. But more broadly, climate change demands smarter approaches and tools to make long-term investments in natural and built infrastructure and in the institutions to manage it. This report details a number of these tools, from decision-making under uncertainty to integrated modeling techniques, to make processes "smarter."

Call to Action Step 2: *Measure and model storage in an integrated way—natural and built, surface and subsurface—to understand, develop, and manage storage as a system with long-term, sustainable, and resilient services as the end objective.*

6.3 WHO NEEDS TO BE INVOLVED?

Closing the water storage gap is a shared challenge. Faced with the growing risks of water insecurity around the world—particularly in the face of the climate crisis—global, national, and regional stakeholders can no longer focus on their own needs in isolation. If we are to achieve sustainable, climate-resilient water storage solutions that sustain generations, a conceptual shift in thinking—anchored in an integrated, systemic approach to planning and managing water storage—is required.

Governments and policy makers have a unique opportunity to lead by setting the criteria for success, advocating for an integrated, systemic approach to storage that begins with a rigorous definition of the water-related problems to be solved, and prioritizing efficient solutions that benefit the largest range of stakeholders. But we all have a role to play.

Utilities, businesses, irrigation schemes, hydroelectric producers, and other bulk users of water services have key roles in defining the problem through identifying their long-term water needs, including for storage services, as well as potential alternatives to them.

Significant investments in storage may have significant trade-offs associated with them, which different stakeholders may have differing views on. The social or environmental implications of different management approaches to built or natural storage (e.g., land-use restrictions) also need to be carefully understood. Similarly, storage services may be most efficiently provided through multipurpose infrastructure provided to multiple and sometimes competing stakeholders. All stakeholders, including those representing the environment, have a part to play in thinking through these trade-offs, as well as clarifying the value, and therefore the economic and financial sustainability, of future investments for them, through joint processes that help produce a shared understanding and more resilient and integrated services in the future.

From decision-makers at water ministries and ministries that are water-reliant, to engineers, ecologists, and academics, to project teams at the World Bank and other international development agencies, expertise and accountabilities vary significantly. Yet achieving resilient, sustainable storage solutions is predicated on a universal shift in thinking, a collective understanding of the new paradigm for water storage, and adoption of the key principles that characterize an integrated approach.

> ***Call to Action Step 3:*** *Engage all stakeholders to define the storage services needed (the "problem") and the trade-offs associated with future investments (the "solutions").*

6.4 HOW CAN STAKEHOLDERS APPROACH STORAGE MORE STRATEGICALLY?

This report suggests an Integrated Storage Planning Framework that could be helpful for developing more—and more sustainable and resilient—freshwater storage in the future. The framework covers three stages: (1) a needs assessment to define the problem; (2) definition of the system and potential solutions; and (3) a decision-making process considering a range of scenarios and uncertainties.

Together, these steps are designed to build the knowledge and the consensus required for investing in improved water storage services for the long term, including in the face of a changing climate. Critically, the framework includes ways to consider whether storage investments are really the best way to address water-related challenges, or whether alternatives should be considered.

At a practical level, this report identifies five major areas for investment in future storage systems (both natural and built), which it summarizes as the "5 R's":

1. Rehabilitating current storage, including restoring natural systems, to improve the effectiveness and sustainability of current storage services
2. Retrofitting existing storage to increase or improve storage services
3. Reoperating existing storage to change the nature of the storage service being provided by current natural or built infrastructure
4. Raising new storage if improvements to current storage systems are insufficient to meet current or future needs
5. Reforming institutions so as to enable the more integrated planning and operation of storage systems into the future

Many countries are likely to need to invest in all these areas, and the report also includes recommendations about how to approach mobilizing finance for storage, as well as how to safeguard the economic returns over time through provisions for operation and maintenance costs and a life-cycle approach.

> ***Call to Action Step 4:*** *Use an integrated planning methodology to identify and prioritize investments in both natural and built water storage and develop an institutional setup that can maintain and operate storage in the public interest for the long term.*

In short, ***What the Future Has in Store: A New Paradigm for Water Storage*** calls on all stakeholders to think differently, plan inclusively, and act systematically to address the water storage challenges of the coming century. It presents a progressively urgent appeal for multi-sector practitioners at every level, both public and private, to begin championing integrated smart water storage solutions that meet a range of human, economic, and environmental needs. Closing storage gaps will require a spectrum of economic sectors and stakeholders to develop and drive multi-sectoral solutions that address the water storage gap holistically, effectively, and efficiently. Done right, a new paradigm for water storage, backed by investment, will create a stronger foundation for sustainable development and climate action and resilience, paying dividends for populations, economies, and the planet through years and generations to come.

Itaipú dam from above. © Mykola Gomeniuk | shutterstock.com

A new paradigm for water storage, backed by investment, will create a stronger foundation for sustainable development and climate action and resilience, paying dividends for populations, economies, and the planet through years and generations to come.

RESOURCES FOR STORAGE PLANNERS

Part II

7 THE INTEGRATED STORAGE PLANNING FRAMEWORK: A STEP-BY-STEP GUIDE

This chapter provides a step-by-step explanation of how to apply the Integrated Storage Planning Framework presented in chapter 3 of *What the Future Has in Store: A New Paradigm for Water Storage,* for those who want to apply some or all of its principles in their storage planning. Please see table 3.2, "Summary of the Integrated Storage Planning Framework," for a synopsis of the process elaborated in this chapter.

7.1 STAGE 1: THE PROBLEM: A NEEDS ASSESSMENT

The first stage comprises a needs assessment of two steps: (A) defining the development objectives related to the problems that need to be solved, and (B) characterizing the water service requirements needed to achieve the development objectives.

7.1.1 Stage 1.A: Defining Development Objectives

KEY QUESTIONS TO ANSWER IN STAGE 1.A

- ***What are the development objectives for the system?***
- ***Who experiences the problems and who may be part of the solution?***

Technical Characterization

The first step entails defining the problems in the system and the development objectives linked to them. For example, if the underlying problem includes flooding, the main development objective may be to reduce the impacts of floods in a specific geography. Typically, development objectives that involve action in the water sector include versions of the following high-level objectives:

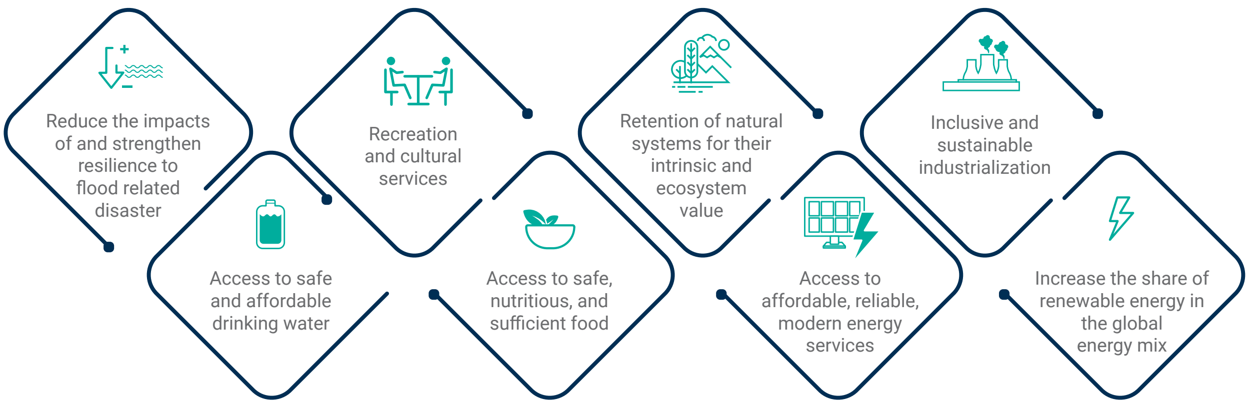
- Access to safe and affordable water and sanitation services for current and future populations
- Food security (access to safe, nutritious, and sufficient food now and into the future) and sustainable agricultural livelihoods
- Inclusive and sustainable industrialization
- Mitigating the impacts of and strengthening resilience to floods
- Economic and efficient means of transporting goods and peoples
- Affordable, reliable, and modern energy services
- Increase share of renewable energy in the total energy mix
- Access to recreation and cultural services
- Retention and upkeep of the health of natural systems for inherent value

By first identifying development objectives (figure 7.1), rather than specific engineering or management solutions, it may be possible to identify other objectives to pursue in parallel, creating greater efficiencies. At this stage, it is also possible to identify the different systems that are involved, directly or indirectly. For example, pursuing sustainable agricultural livelihoods in a district will, at a minimum, involve the agronomic system and agricultural supply chain for the area and touch one or more hydrological basins.

Tools

Some development objectives may already be well known; in some cases, a recent or ongoing crisis such as a flood or drought may be driving the planning process. To identify other, co-existing needs, existing multi-stakeholder planning processes such as a national or subnational development plan or strategy are a logical starting point. Often, such plans have already been narrowed down to an actionable scope with spatial boundaries in time-bound agency business plans or sectoral plans, such as integrated water resources management (IWRM) management plans, power system master plans, disaster risk

FIGURE 7.1 Development Objectives Enabled by Water Storage Services



Source: Original figure for this publication.

management plans, or city-level plans. In the absence of plans, or to identify objectives that may not yet be included in them, contact with professionals in other water-using sectors may help identify objectives.

Stakeholder and Impact Analysis

KEY QUESTIONS FOR EACH IDENTIFIED STAKEHOLDER

- *Where in the geography of concern are they located?*
- *To what extent do they use, restore, pollute, or rely on the hydrology of the system?*
- *Is this interaction sustainable or at risk?*
- *How do their actions impact other stakeholders?*
- *How do other actors impact this stakeholder?*
- *What tools are available to modify the stakeholder's behavior or environment, if needed?*
- *For this stakeholder, what are some of the related development objectives that potentially support or conflict with the objective in focus?*

Characterize stakeholder needs, interests, and impacts for each development objective. Options for addressing the development objective at hand will affect a set of stakeholders throughout the system, including direct beneficiaries as well as stakeholders further upstream or downstream who influence the status quo or who will be affected by changes introduced in the system. Stakeholders also include other actors in the public or private spheres whose actions either advance or constrain the development objective being pursued. The environment should also be considered a stakeholder at this stage as elements of the environment, such as certain species, may be the intended beneficiaries of water resources management interventions (noting that risks and impacts to the environment are introduced in Stage 2.A, which aims to build understanding of the existing system). It is important to identify and map the stakeholders, how they interact with the system, and whether they would benefit or be disadvantaged by possible changes. Depending on the level of study/analysis, direct contact with stakeholders will likely be needed early in the process to ensure that hypothesized needs and preferences are true to reality (while balancing the need to control expectations with affected communities).

Communities and local government have an important role to play at this stage. Local experiences are critical to filling gaps in official statistics during the needs assessment, and local knowledge around the performance and interlinkages of existing systems is crucial to problem definition. Civil society organizations (CSOs) may also have technical expertise that can help communities articulate the challenges faced and even serve a brokering function to bring different stakeholders together to address the issue. For example, in the creation of the Upper Tana-Nairobi Water Fund in Kenya, CSO partners and foundations were integral in bringing to reality a project to incentivize upstream smallholder farmers to conserve and restore the natural water storage capabilities of the catchment (wetlands and forests), which supplies bulk water, including for industrial use, to the city of Nairobi downstream, as well as flows to several hydropower stations in the basin. A comprehensive analysis of benefits and costs to the various private and public sector stakeholders was also a critical part of creating a business case for the project and establishing its viability (TNC 2015).

Tools

Stakeholder analysis can be carried out with the aid of a stakeholder map, which enables identification and prioritization of stakeholders and their perspectives and is helpful to inform communication and consultation plans, which will be useful while advancing through the stages of the framework. Depending on the complexity of relationships and power dynamics, a political economy analysis may also be a useful and informative part of the stakeholder analysis at this stage. In subsequent stages of the framework, we consider environmental risks, impacts, and opportunities in the areas of concern, but at this stage, it is important to remember the environment is also a water user that will be affected by the preferences and actions of other stakeholders in the system. Resources such as the "Engaging Stakeholders in Water-Energy-Food-Environment Systems Assessment and Planning: A Future DAMS Guide" can assist with these analyses (Dye, Hulme, and FutureDAMS-Consortium, n.d.).

7.1.2 Stage 1.B: Characterizing Water Service Requirements

Technical Characterization

After identifying the underlying problem and mapping the stakeholders, the next step is to determine the water service requirements for meeting the specified development objectives now and into the future. *Water service requirements* is used as a broad term describing the supply and control of water needed to support the development objectives and outcomes identified in Stage 1.A. At Stage 1.B, thinking about water service requirements instead of technical interventions or infrastructure facilities enables holistic, system-wide planning for getting desired benefits to intended beneficiaries. Water service requirements for the development objectives listed above could include:

- Water supply for drinking and domestic use, crops and livestock, industry, and so on expressed as an amount
- Flood protection and attenuation of excess flows for disaster risk reduction
- Control of flow and level for navigation, hydropower generation, or recreation and cultural services
- Environmental flows for ecosystem preservation and restoration (including prevention of saline intrusion)

These requirements should be expressed in volumetric, temporal (when and how often), and geographic dimensions.

Identifying parameters that can assist with decision-making. Considering the questions above, water service requirements can be more specifically described with key

KEY QUESTIONS TO ANSWER IN STAGE 1.B

- *What are the water service requirements for meeting development objectives in the system (present and future)?*
- *What are the service attributes of the water requirements?*
- *How do these water requirements relate to different stakeholders?*

MORE SPECIFIC GUIDING QUESTIONS USEFUL IN UNDERSTANDING THE NATURE OF THE REQUIREMENT

- *Is the problem one of too much water or too little?*
- *If too little, then what is the additional volume of water needed?*
- *Is the water that is needed going to be consumed (removed from the water resources system after being used) or is it a non-consumptive use (water returned to the water resources system after being used)?*
- *When and how often (inter-annual, seasonal, periodic) is additional water needed?*
- *Where geographically is the water required?*
- *Is it a temporary need or will the water be required in perpetuity?*
- *If too much water, what is the volume of excess?*
- *When and how often does this excess occur?*
- *What spatial area experiences excess water?*
- *How is the need for more water or the impacts of excess water likely to evolve in the future given climate change, urbanization, and any new economic aspirations?*

TABLE 7.1 Water Service Attributes

	WATER SERVICE ATTRIBUTE	DEFINITION	PERFORMANCE INDICATOR	UNIT (EXAMPLES)
1.	**Reliability**	Degree to which water management options consistently succeed in serving all intended purposes	—	—
1a.	Assurance levels	Performance reliability of the water management option	Average time between consecutive performance failures (predicted probability or historic)	Years, months, days
1b.	Impact of unreliability	Magnitude of performance failure if underlying option fails to support service delivery	Size of impact if option fails to deliver on intended purpose (can be graded by percentage of failure)	Hectares of crop lost, financial/economic cost
2.	**Controllability**	Degree to which water management may be controlled or operated for intended purposes	—	—
2a.	Volumetric control	Degree to which volume of water can be controlled	Least amount of water that may be released	Cubic meters
2b.	Geographic control	Geographic area that can be serviced by underlying water management option	Service area that can be supported by the option	Square kilometers
2c.	Temporal control	Frequency with which underlying water management option can be re-mobilized for service delivery	Average time needed between consecutive operations or for recharge	Years, months, days
3.	**Adaptability**	Ability to adjust or modify water management option to new conditions, uses, or purposes	Number of other uses or conditions the water resources management option could be modified for	Number
4.	**Vulnerability**	Susceptibility to and magnitude of potential damage from hydroclimatic hazards	—	—
4a.	Physical vulnerability	Susceptibility to flood and drought hazards (influenced by design parameters, location, and operating condition)	Likelihood of significant damage or total system failure	Low, moderate, substantial, high
4b.	Magnitude of vulnerability	Magnitude of consequences of significant damage or total system failure	Extent of potential impact	Hectares of crop lost, kilowatt-hour of hydropower foregone, potential loss of life, financial or economic cost
5.	**Quality**	Degree to which freshwater is free of contaminants that negatively affect its uses	—	—
5a.	Salinity	Amount of dissolved salts in the water body or source	Concentration of dissolved salts	Conductivity values
5b.	Pollution	Presence of pollutants from point and nonpoint sources	Concentration of pollutants such as heavy metals, harmful chemicals, bacteria, nutrients, and oxygen-depleting substances	pH values, total dissolved solids levels, biological oxygen demand, quantitative mass measurements
5c.	Turbidity	The relative clarity of freshwater	Concentration of suspended sediment	Quantitative mass measurements

Source: Original to this publication.
Note: — = not applicable.

KEY QUESTIONS

- *Which of the stakeholders identified in Stage 1.A have the water service requirement, and how would it affect their socioeconomic and environmental well-being?*
- *What are the opportunities available to them once the water service requirement is met, and how can these potential benefits be measured?*
- *What are the trade-offs created by serving this set of stakeholders versus another?*
- *Is it possible to disaggregate the stakeholders at this stage by gender, occupation, income level, or other characteristics to understand how meeting the water service requirements could serve to narrow inequalities?*
- *What are the water service requirements that support biodiversity and ecosystem functioning?*

parameters that will enable later comparison of different water management options, including storage, in terms of quality of service. In the framework, these parameters are referred to as *water service attributes* (table 7.1). In many cases, water storage, both natural and built, enhances these attributes:

- **Reliability,** which measures the degree to which water management options consistently succeed in serving all intended purposes
- **Controllability,** which measures the degree to which water management may be controlled (volumetric, spatial, and temporal) over service delivery for intended purposes
- **Adaptability,** which measures the ability to adjust or modify a water management option to new conditions, uses, or purposes (GWP and IWMI 2021)
- **Vulnerability,** which measures the susceptibility to and degree of potential damage from hydroclimatic hazards
- **Quality,** which measures the degree to which water is free of contaminants that negatively affect its uses

Stakeholder and Impact Analysis

Clarify water service requirements. In Stage 1.A and the identification of the development objective to be addressed, stakeholders that would potentially impact or be impacted by the actions taken were identified. Having ascertained the water service requirements for achieving the specified development objective and the desirable water service attributes that correspond to those requirements, it is important to then consider how those affect the different stakeholders.

In a full-scale options assessment, this would entail additional consultations to verify assumptions with stakeholders. As in Stage 1.A, local knowledge and experience brought by communities, local government, and CSOs are valuable during this process. It is also important to consider the full range of public and private stakeholders identified in Stage 1.A, including vulnerable groups whose views and needs may be underrepresented.

7.1.3 Stage 1 Outputs

Clearly defined development objectives and the water service requirement(s) to meet those objectives to deliver present and desired future uses of water. This initial characterization of needs supports decision-makers in identifying which enabling services of storage (described in chapter 1) possess desirable service attributes and are, thus, able to meet the water service requirements.

A needs assessment: Stage 1 concludes with an assessment that specifies water service requirements for the system, characterization of stakeholder interests and capabilities, and the enabling environment. It provides an initial characterization of the various services of storage that will support achievement of water security goals.

7.2 STAGE 2: THE SYSTEM: ESTABLISHING THE BASELINE AND UNDERSTANDING SOLUTIONS

The second stage of the framework relates to establishing the baseline by characterizing the current system and the potential for additional water management options or other solutions. This is an important step after characterizing water service requirements but before beginning to evaluate different investment or management options. This characterization of the system enables better understanding of existing supply-side and demand-side water management measures, the extent to which existing measures engage and benefit stakeholders, and what alternative or complementary water management actions may feasibly be scaled up to contribute to meeting development objectives. While this framework focuses primarily on storage-related measures, it recognizes the need to characterize and evaluate storage-related measures alongside a broader suite of water management measures, including demand control, quotas and enforcement, non-traditional water sources, and more, as well as to consider measures outside the water sector (e.g., alternative sources of energy generation).

7.2.1 Stage 2.A: Taking Stock of the Current System

KEY QUESTIONS TO ANSWER IN STAGE 2.A

- *What water security measures, storage and non-storage, are in place in the current hydrological system?*
- *What are the systems that need to be considered, beyond the water system?*
- *To what extent do the existing water management systems engage and benefit or harm different stakeholders?*

Technical Characterization

Characterizing the current hydrological system starts with understanding the physical system as well as the water service requirements supported by the components of that system. This assessment provides data on how the current freshwater system works, including availability of water, demand for water, a model of how water is stored in the system, how it is managed, and how other elements of the system interact. Existing built and natural infrastructure are considered here, as well as the contributions from the system to achieving the desired water service requirements (using comparable measures of performance such as those in table 7.1). This should not only cover infrastructure owned or operated by the public sector but also, to the extent possible, all the infrastructure in the basin regardless of ownership. This is sometimes referred to as a "baseline." The characterization should include consideration of future trends, including climate change. Box 7.1 provides an example of determining the scale of the system for urban flood management.

Supply-side characterization: **Identifying the supply-side water management measures in place in the system and services they provide, including all forms of infrastructure and interventions that contribute to the collection, retention, conveyance, treatment, desalination, storage, and distribution of water as well as monitoring of the resource.** These measures aim to (a) increase the quantity of freshwater supply (e.g., desalination and treatment); (b) provide access to bulk water (e.g., water distribution infrastructure); and/or (c) manage and alter water availability through space and time (e.g., storage and flood retention measures). This should include the level of functionality of the existing system.

Demand-side characterization: Examining current and future water demands as well as measures in place to manage water demand. Water demand is the volume of water that is needed to satisfy all water service requirements in a system. This includes all different forms of water demand by different sectors, such as water demand for irrigation, industry, navigation, and environmental flows. An assessment of water demand includes current needs and projected future needs, taking into consideration population growth, economic growth, industrialization and other sectoral shifts, and improvements in technology and efficiency. It is important to distinguish between consumptive and non-consumptive water demand as the latter does not necessarily diminish the amount of water available for other uses. Water demand varies across space and time and, in many cases, follows a seasonal pattern, especially where demand for irrigation water exists. Measures to control water demand and constrain its growth include pricing, quotas, and loss reduction measures, among others.

Identifying other systems. Water resource management involves several systems beyond the physical hydrology, including other natural resource systems, socioeconomic systems, and administrative and institutional systems (Loucks et al. 2017). At this stage, a brief screening is necessary for other elements that may need to be considered, for example, power transmission and trade, agricultural management systems, or other institutional systems, such as authorities involved in disaster risk management. Relevant information on these systems can be gathered, and stakeholder assessments updated accordingly.

BOX 7.1 **Urban Flood Management**

How do you know which scale to address in system planning? The scale of storage planning itself is determined by the development objective being pursued and the stakeholders and jurisdictions involved.

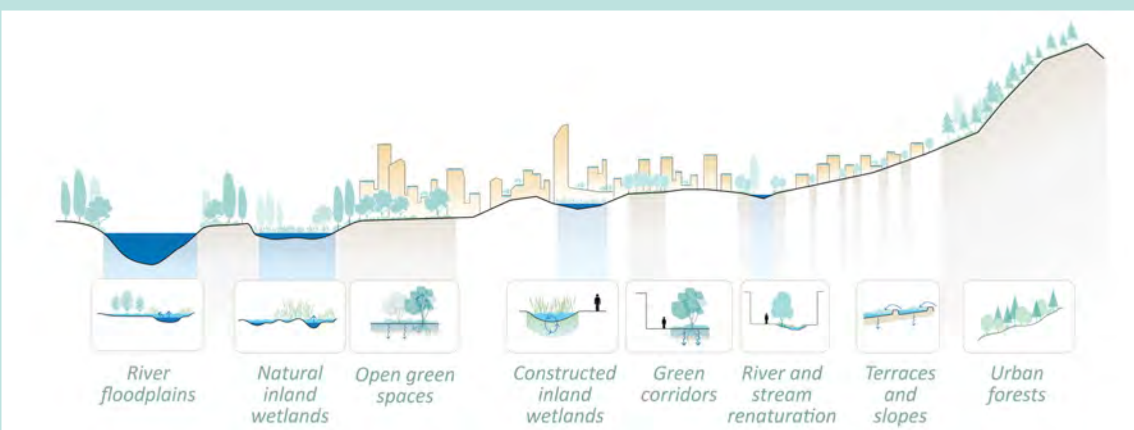
In pursuing objectives, the system of concern should encompass (a) intended beneficiaries and the location of their service needs, (b) upstream and downstream actors who influence the service delivery challenge, (c) a uniform administrative/policy jurisdiction, and (d) parts of the watershed that make implementation of solutions institutionally and technically feasible. In the case of dams, areas of planning may include the catchment area (where water is impounded), the command area (which is irrigated), and downstream of the irrigated area.

In the case of urban flood protection, measures can be pursued across three scales to maximize disaster risk reduction: river basin, city, and neighborhood.

At the river basin scale, it is important to recognize the interconnectedness of communities and the importance of integrated catchment management approaches to address flooding and water resource challenges. Basin scales can be used to tackle the problem near the source, outside of the city where a problem may be felt and before it reaches the city (e.g., upstream forests to intercept and slow floodwater, and river floodplains to enhance storage and reduce flood risk downstream).

At the city scale, solutions include measures that seek to complement and strengthen urban land-use planning and support disaster risk management. The landscape and ecological structure of the city, together with the unique challenges faced by city residents, determine the suitability and potential of solutions (figure B7.1.1), such as constructed wetlands to collect and store water runoff and open green spaces or parks throughout the city to add infiltration capacities.

FIGURE B7.1.1 City-Scale Nature-Based Solutions



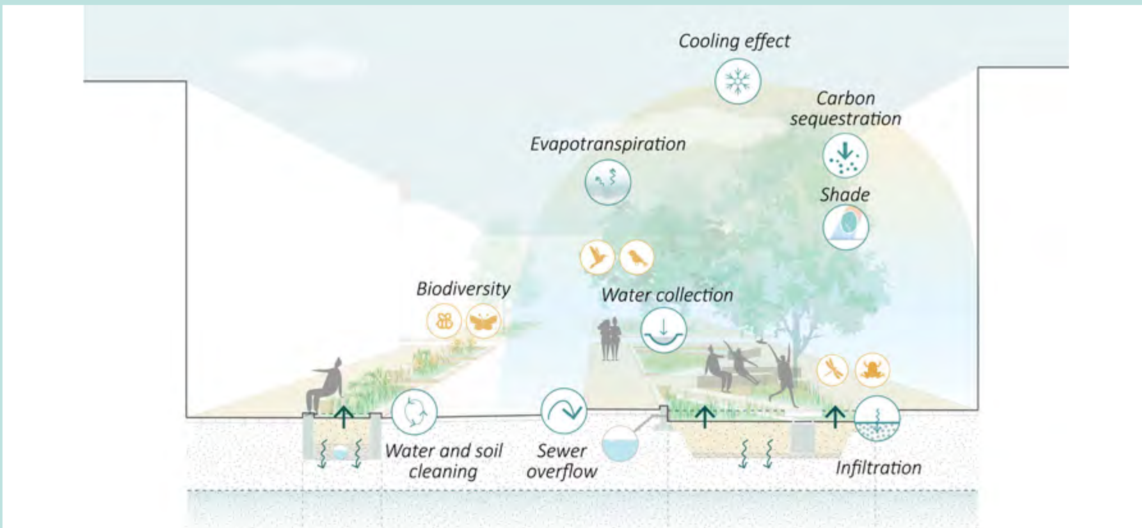
Source: World Bank 2021a.

At the neighborhood scale, solutions can help address resilience challenges, including measures in buildings, streets, and open public spaces. For example, smaller-scale interventions can build resilience by increasing stormwater retention capacities and reducing the "heat island" effect. These solutions can be very effective for local rainwater collection, to mitigate impacts of air, water, and soil contamination, and to reduce heat levels in cities by providing shade. Working at the

BOX 7.1 **Urban Flood Management (cont.)**

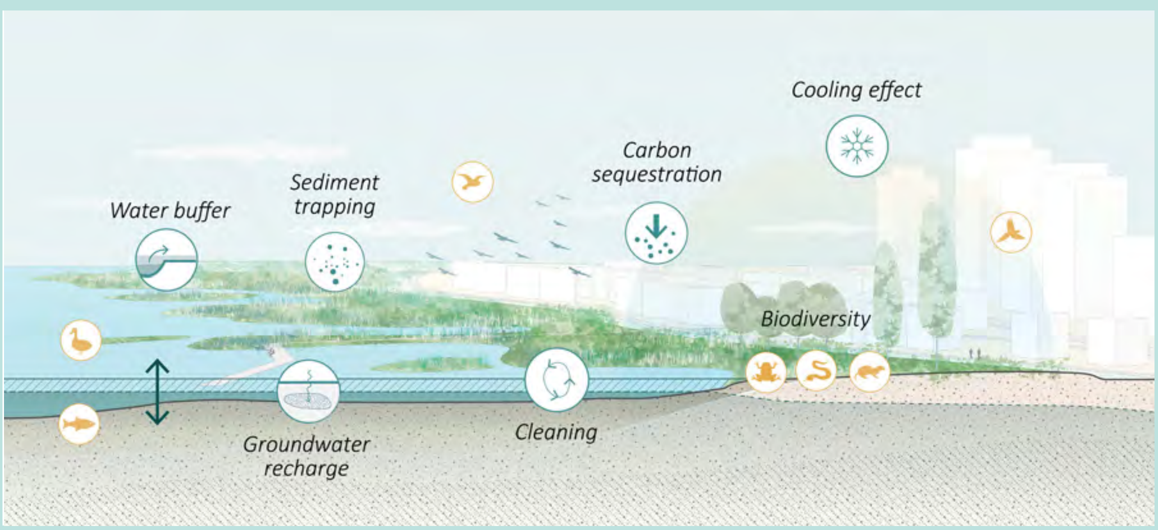
neighborhood level can relieve pressure on existing local infrastructure such as stormwater drains. Examples of solutions at the neighborhood scale include green roofs, green facades, private gardens in combination with green streets; retention basins, rainwater retention ponds, or green water squares to store water; and small-scale rainwater catchment and drainage interventions such as bioswales (e.g., bioretention areas [figure B7.1.2] and constructed wetlands [figure B7.1.3]).

FIGURE B7.1.2 Bioretention Areas



Source: World Bank 2021a.

FIGURE B7.1.3 Constructed Wetlands



Source: World Bank 2021a.

Tools and Data

Water accounting is a useful way to approach the characterization of a current situation, where a proper accounting of both supply and demand within the system is needed to understand how much water is required to meet the system's requirements, where, and why (box 7.2). However, as the framework is intended to be an upstream and largely desktop phase, planners will need to rely on data and tools that can be gathered relatively easily. This could include (a) existing storage mapping and quantification literature and datasets (outlined in the previous chapters); (b) existing planning documents from river basin authorities, cities, and industries (c) existing global or regional datasets on precipitation, streamflow, and land cover, and (d) new high-level data collection from remote sensing or similar methods.

Stakeholder and Impact Analysis

Characterize the extent to which existing water management systems engage and benefit stakeholders. With greater understanding of the water management system, it is possible to refine the mapping of stakeholders and their needs. Initiated under Stage 1, this includes a broad range of stakeholders, including those dependent on water for lives and livelihoods, those with spiritual and cultural ties, and those that can represent environmental interests. If relevant, the private sector could also be considered during this exercise to ensure that privately owned assets that are part of the storage and hydrological system are accounted for and that industrial water demands are quantified, including where the potential exists for new industries to enter, or existing industries to expand in

BOX 7.2 **Water Accounting**

Water accounting is the "*systemic study of the current status and trends in water supply, demand, accessibility and use in domains that have been specified*" (FAO 2012). It allows for the systematically acquiring, quality controlling, and analyzing of water-related information and evidence, which in most cases will come from diverse independent sources that can be used for (FAO 2017):

- Situational analysis
- Social and institutional learning
- Evidence-informed planning
- Development and updating a common information base
- Water allocation, regulation, and conflict resolution
- Challenging factual errors or biased views
- Evaluating anecdotal evidence, expert opinion, and folklore
- Awareness-raising

Water accounting can help with the understanding of the impacts of water use in a basin by multiple sectors and the natural environment, and can evaluate the way changes—natural or human caused—in one part of the hydrologic cycle may affect other elements of the cycle in natural, disturbed, or engineered environments (World Bank 2020d). This is especially important when considering options for water storage, as this tool considers not only the impacts on the water itself but also the capacity, condition, and operations and maintenance (O&M) of the water storage in the basin.

Very much a mechanism that can support the proposed framework, water accounting helps answers questions such as:

- *What are the underlying causes of imbalances in water supply (quantity and quality) and demand of different water users and uses?*
- *Is the current level of consumptive water use sustainable?*
- *What opportunities exist for making water use more equitable or sustainable?*

Source: FAO 2017.

KEY QUESTIONS

- *To what extent do existing water management measures and infrastructure engage and benefit stakeholders?*
- *What are the stakeholder incentives, capabilities, and institutional systems that exist to improve functionality of existing water management systems?*
- *How are existing storage measures used/not used for their intended purpose, or how may they serve alternative/additional purposes?*
- *To what extent do existing storage measures positively or adversely impact (or exacerbate vulnerabilities for) certain stakeholders?*

GUIDING QUESTIONS TO CHARACTERIZE IMPACTS OF EXISTING SYSTEMS ON THE ENVIRONMENT

- *To what extent is the natural environment surrounding the area of interest altered or degraded?*
- *Does the area of interest have protected status or is it considered to be of high conservation value?*
- *Does the area form part of the habitat for endangered or endemic species?*
- *To what extent are surface water flows regulated by existing infrastructure?*

response to better water management in the area of study. For example, private irrigation canals or fallow fields can serve as conduits of intentional groundwater recharge, if managed as part of the system.

Characterize impacts of existing water management systems on the environment. This is an opportunity to identify those elements of the environment in the area of interest that have scientific, economic, social, or cultural significance, as well as the beneficial or detrimental impacts of current water management infrastructure and measures on them. This will enable early identification of environmental risks to the system and how potential measures may remediate, exacerbate, or create them.

Characterize existing challenges in the water management system. It is important to consider ongoing and potential future challenges facing delivery of water service requirements and achievement of objectives. Constraints may be natural (external variables relating to hydrology and geography), technical (engineering or ecological or nature-based human interventions to control nature), political/institutional (governing interactions between the natural and socioeconomic systems), financial (resources available, public and private), behavioral (incentives and cultural norms), or relating to capacity (institutional and workforce).

Tools and data. This characterization of the existing system can be aided by a broad analysis of the benefits and costs to the different users of water-related services facilitated by water management measures. Economic and environmental aspects could be considered as well as existing and potential distributional impacts. These impacts may also be felt beyond intended beneficiaries of the measures. If strategic/basin-level studies such as strategic environmental assessments (SEAs) or cumulative impact assessments (CIAs) have been carried out in the area, these may have identified valued ecosystem components (VECs), which may have included preliminary screenings of environmental and social risks. Where such detailed studies do not yet exist, public datasets and geospatial platforms from CSOs and international organizations may be useful, such as the Integrated Biodiversity Assessment Tool (IBAT), the Map of Life, Global Biodiversity Information Facility, Protected Planet (World Database on Protected Areas), the Key Biodiversity Areas platform, and the Global Invasive Species Database, among others.

Accurate assessment of supply and demand (Stage 2.A) and characterization of how these factors may be altered (Stage 2.B) are crucial to inform whether the system is in need of "new" infrastructure, or if there are opportunities with interventions and policies that focus on demand management (in the case of a water supply gap) or other non-structural measures.

7.2.2 Stage 2.B: Solutions: Identifying Additional Options

Technical Characterization

Identify other potential options to meet development objectives—through water and beyond. After identifying the development objectives, prioritizing water service requirements, and looking at the current system, it is possible to

KEY QUESTIONS TO ANSWER IN STAGE 2.B:

- *What are the additional options for meeting the water requirements of the system, including enhanced performance and the options for new development?*
- *Who will benefit or be harmed by each option?*

see where supply-demand gaps exist and whether there are needs for additional options—through water management or more broadly—to support achievement of objectives. Some development objectives, such as access to water supply or reducing flood risks, are often inextricably water-dependent and require water-related solutions. In other cases, water storage may be needed to meet water service requirements; what is perceived to be a water supply gap may really be a water storage gap.

Identification of alternative water management solutions can be informed by the water service requirements and may not involve water or water storage. Alternative solutions may exist outside of the water sector for many water-related development objectives. For example, power generation or transportation of goods and people may be met by non-water alternatives, depending on the circumstances, where solar or wind power may be competitive with run-of-river hydropower or where rail transportation may be as effective as restoring or improving river navigability. The details of the alternatives, however, must be explored to verify the needed alignment between scale, scope, and timing of the water-dependent choice and the alternative. For instance, while solar power or wind may be able to generate the same amount of electricity, they may not meet requirements for reliability and grid integration. In other cases, water management options can meet water service requirements without the need for storage. For example, run-of-river hydropower may enable the generation of electricity at acceptable levels of reliability without water storage.

Getting More from Current Storage

Opportunities to gain more storage services from the storage that already exists may include:

1. **Reoperation:** The modification of storage operations for improved management (efficiency gains), which might include changing the timing of water releases from controllable infrastructure, managing for synergies between different types of storage, or minimizing storage losses from evaporation. This may also include creating new connections between existing storage so that they may be operated as part of a broader system.
2. **Rehabilitation:** The restoration of current storage to improve storage capacity or performance. Rehabilitation can extend the life of existing storage capacity and defer investment in new storage. Restoration of original capacity or slightly improved capacity could be achieved through addressing structural defects, sediment removal, increasing the flow rates of managed aquifer recharge (MAR) sites, and environmental restoration of natural storage, among others.
3. **Retrofitting:** The upgrading or augmentation of capacity at existing storage facilities or enabling new uses of the facilities. This could be achieved through raising the height of dam walls or adding new hydromechanical or electromechanical equipment to serve different objectives or different customers to make overall gains in the value of storage services.

Exploring these potential gains could be guided by the types of questions and examples included in table 7.2.

This type of analysis establishes "first order" estimates of potential increases in storage services from current storage systems. Some of these options may be low-hanging fruit and therefore worth pursuing immediately, whereas others might require further consideration. This could include deeper investigation (e.g., more technical studies on the potential for expanding groundwater extraction and recharge) and/or initial data in the modeling and scenario stage to compare these options with new storage development options (box 7.3).

Finding or Developing Additional Storage

In Stage 2.B, it is important to not only include previously identified storage options that exist in master plans or other sector planning documents but also to look beyond at the full range of available storage types: natural and built; surface and subsurface; large and small; and centralized and distributed. Depending on the

TABLE 7.2 Gaining Additional Storage Services from Current Systems

TOPIC	ISSUES	"CITY X" EXAMPLES
Rehabilitation of Natural and Built Storage	Does the current storage system include all the (significant) actual freshwater storage in the service area of interest? If not, it would ideally be added to the picture. If it does, could better management, repurposing, or rehabilitating current storage meet the projected water storage gap?	City X has its storage system that it controls but does not yet consider the amount of water stored within the natural landscape or private agricultural dams within its watershed. If there is, in fact, significantly more storage in these other places, the question is whether, and under what conditions, City X can leverage these other water stores to deliver services. City X has access to some groundwater. Is it possible to increase sustainable yields, either permanently or temporarily, during dry seasons or years? Has the full potential of managed aquifer recharge been exploited yet?
Retrofitting or Reoperating Existing Storage	Could retrofitting or reoperating current storage produce additional gains, and could related costs be suitably compensated for? Would physically connecting existing storage provide greater resilience?	Farmers control a significant volume of storage upstream of City X and use it to irrigate crops. In an average year, the returns to crops are greater than the marginal cost of city water supply, but in particularly dry years, it may be considerably cheaper for the city to buy stored water from farmers than invest in other alternatives. Upstream hydropower facilities are being optimized for energy production. Under what circumstances would it be economic to optimize from a water storage/flood protection perspective as well?
Reoperation	How is this storage operated now, by whom, and what gains could be affected from its reoperation?	City X's upstream natural landscape storage is being impacted by alien vegetation that is accelerating evapotranspiration. Control over this landscape is shared between private and public parties. Can City X influence governance structures to reduce the negative impacts of alien vegetation on natural storage and flows?
Environmental and Social impacts (across all solutions)	Can any environmental and social impacts or distributional effects be suitably mitigated or compensated for?	If changed behavior by farmers or landholders in watershed areas is required, which results in lost livelihoods, can this be effectively compensated for? Have land rights, private ownership, and applicable regulations in the region been considered?

Source: Original to this publication.

services desired, a combination of options may be worth examining. Table 7.3 outlines some of the key resources that could be considered in identifying additional storage opportunities.

For most forms of natural storage, "new storage" assessments would involve understanding the potential of the natural environment to retain and release freshwater in a somewhat predictable (if not actually controllable) way. If natural storage options are not already included in formal planning documents, broad scoping studies may need to be undertaken.

The process outlined in this stage aims to encourage water planners to consider the full range of potentially feasible options; it does not promote an exhaustive consideration of options. Guided by the water service requirements and performance indicators outlined in Stage 1.B (table 7.1), options that are obviously unable to meet the needs at hand or are indicated as having unacceptable risks or impacts may be discarded to focus on those options that are promising, even if further study is needed before an informed decision can be made.

Stakeholder and Impact Analyses

Characterize the extent to which additional water security and storage options positively or adversely impact stakeholders: Similar to the stakeholder mapping exercise conducted to characterize stakeholder interests related to the current system, stakeholder interests for additional

BOX 7.3 Comparing Storage Options Across Storage Types

Denver, Colorado, and surrounding cities draw water supply from the South Platte River, a tributary of the Colorado River. With the growth of the population in the Front Range, the Colorado General Assembly, in coordination with the Colorado Water Conservation Board, the Colorado Division of Water Resources, and the South Platte Basin and Metro Roundtables, commissioned a study to look at opportunities to increase water storage.

The resulting South Platte water storage study compared a range of water storage options, including groundwater recharge, expansion of existing reservoirs, and new reservoirs. One aspect of the study was to quantify the amount of "*available water for storage*" at various locations, considering both the hydrological supply, demands, and the legal obligations of the state to comply with the Law of the Colorado River, given its position as an upstream state. The study then compared storage options, as well as packages of storage options, including mainstream dam versus upper basin storage and mid-basin storage versus packages of aquifer storage. For each of these packages, the study then rated performance across a range of indicators, including whether the package met firm yield requirements, whether they enhanced stream flows overall, and at times of low flows at the border (to meet legal water sharing requirements), the potential for flood attenuation, environmental factors, and recreational provisions, among others. By comparing types of storage across each other, several important conclusions were reached, including:

- *"Combinations of storage options working conjunctively can provide significantly more benefit than individual options. A combination of upper basin and lower basin storage concepts rivals the large mainstem dam option for firm yield benefits. However, there will be a reduction in efficiency as the number of projects goes up."*
- *"Aquifer storage projects are more limited by recharge and recovery rates rather than storage volume. Typical aquifer storage projects are designed as supplemental supply sources, not as projects to recharge large volumes of water diverted during peak spring snowmelt periods. This results in lower firm yield and does not attempt maximize use of potential storage capacity as occurs with surface reservoirs. However, a related benefit is that aquifer storage projects are relatively low cost and can be scaled up over time (not constructed all at once). These unique characteristics make aquifer storage projects difficult to compare to surface water storage projects."*
- *"Storage options lower in the basin tend to be more efficient (better storage yield ratio) because there is more water available. However, they are further from the main demand centers."*
- *"Using existing irrigation canals to fill storage sites could significantly reduce infrastructure costs for some concepts. Partnerships with irrigation companies and available canal capacities should be investigated further."*

While these findings are basin and context specific, they illustrate the value of considering and comparing a range of storage options in various combinations, to better understand how various storage options can be used to best meet the needs of populations. Further, some of the findings related to comparing surface and groundwater storage may hold across basins.

The tools and methodologies used in the study may be of use to others undertaking similar studies, including the selection of attributes (or indicators) used to evaluate storage options.

Sources: LRE Water 2017; C. Nobel, LRE Water, interview with World Bank, January 19, 2019.

storage options should also be assessed. This characterization should be conducted for both retrofitting current systems as well as for any new elements of the system that are identified. This mapping exercise should characterize the main benefits for the primary interest groups, those related to the water service requirements and attributes in particular. It should also examine existing water allocations and rights, the incentives and perceptions of stakeholder groups, and the benefits received by specific groups. Distributional impacts of proposed options should

TABLE 7.3 Identifying Additional Storage Opportunities for Core Storage Services

STORAGE OPPORTUNITY	CORE STORAGE SERVICES	POTENTIAL DATA SOURCES	METHODOLOGICAL REFERENCES
New groundwater	●	Previous studies of groundwater Regional and global datasets The Global Groundwater Information System (GGIS) maintained by the International Groundwater Assessment Center (IGRAC), available at: https://www.un-igrac.org/global-groundwater-information-system-ggis	Resources on groundwater assessments from IGRAC: https://www.un-igrac.org/areas-expertise/groundwater-assessment
Managed aquifer recharge (MAR)	●●	Some wide-area assessments of MAR or Underground Taming of Floods for Irrigation (UTFI) potential have been developed based on geological maps and remote sensing approaches	MAR: https://gripp.iwmi.org/natural-infrastructure/water-storage/ UTFI: https://gripp.iwmi.org/natural-infrastructure/water-retention-3/underground-taming-of-floods-for-irrigation-utfi-2/
Sand dams and subsurface dams	●	Local knowledge and physical surveys At the sub-catchment level, desktop feasibility can be established with the help of GIS and remote sensing	For Africa, the World Agroforestry Centre developed an atlas of possible water harvesting opportunities, including sand dams and subsurface dams: "Mapping the Potential of Rainwater Harvesting Technologies in Africa: A GIS Overview on Development Domains for the Continent and Nine Selected Countries" Excellent Development maintains a knowledge hub on sand dams and has published a manual on sand dams
Flood channels, floodplain storage, and polders	●	Global high-resolution data on floodplains by GFPLAIN	Guidance on Floodway Analysis and Mapping by US Federal Emergency Management Agency (FEMA) Room for the River Programme in the Netherlands European Union (EU) resources on environmental options for flood risk management
Constructed wetlands and urban sponges	●	Land-use maps Estimates on the source and volume of water to be stored (stormwater, wastewater)	A Catalogue of Nature-Based Solutions for Urban Resilience A Manual for Integrated Urban Flood Management in China, featuring China's Sponge City Initiative
Watershed management and sustainable land management	●●●	Local knowledge and physical surveys At the sub-catchment level, desktop feasibility can be established with the help of GIS and remote sensing	Global Database on Sustainable Land Management with documented practices from all over the world WOCAT database and Sahel Water Harvesting Tool -https://sahel.acaciadata.com/

(table continues next page)

TABLE 7.3 Identifying Additional Storage Opportunities for Core Storage Services (cont.)

STORAGE OPPORTUNITY	CORE STORAGE SERVICES	POTENTIAL DATA SOURCES	METHODOLOGICAL REFERENCES
Dams and reservoirs	●●●	National and regional water resources development plans Dam safety inspection reports Systematic high-resolution assessment of global hydropower potential by the Delft University of Technology Global pumped hydro atlas by the Australian National University	The Food and Agriculture Organization of the United Nations (FAO) Manual on small earth dams World Bank Good Practice Note on Dam Safety and associated technical notes Hydropower Sustainability Guidelines and Assessment Tools

- **Improving the availability of water during drier periods**
- **Mitigating the impacts of floods**
- **Regulating flows for other purposes: such as hydropower, transportation, or recreation**

Source: Original to this publication.

be analyzed, as well as opportunities for affected stakeholders to share in the benefits of the options under consideration. Impacts on stakeholders should be considered across a range of geographies, as projects can have varied impacts across geographic areas. It is also valuable to identify the different time frames of interest for each stakeholder and the potential differences in access to information and technology. It is important to identify these variables that will determine the practical capacities and interest of stakeholders to contribute to solutions, including the willingness and capabilities of private sector actors to contribute with financing, knowledge, and technology. Stakeholder mapping should be conducted in consideration of the full system, taking into account not only the interests of individual actors in the current system and additional options but also how those interests would interact with various permutations of additional water security and storage options. The stakeholder mapping could also include identification of the degree to which different stakeholders will be involved in the planning process. Levels of interaction can vary from informing stakeholders to consulting with them to collaborating with them or empowering them to do the planning directly.

Characterize the potential impacts of additional water security and storage options on the environment: As with the stakeholder mapping exercise, a preliminary screening of environmental impacts should be carried out. This is an opportunity to pre-emptively identify beneficial or detrimental impacts of additional water management infrastructure and measures on the environment and will enable early identification of cumulative impacts from the options identified, allowing planners to understand how introducing those changes may remediate, exacerbate, or create environmental risks.

7.2.3 Stage 2 Outputs

A model (or linked models) of the current system: The model will include current availability of water across sources, current and expected changes in water demands, and an understanding of how well the existing system is serving and can serve those requirements. Resulting from this is an indication of whether there are gaps between the supply and demand of water services to meet existing and future requirements, and whether additional water storage is needed in the system.

A set of potential solutions: In considering additional water management options, including storage options, following the two-part scoping exercise should yield a broad set of solutions, including options to get more out of existing storage and options for new, additional storage across the range of available storage types.

A stakeholder map and environmental screening: Stage 2 ends with a stakeholder map and environmental screening, which are further developed and may begin to reveal some options as feasible or infeasible from a social, environmental, economic, or technical capacity perspective. Outputs from Stage 2 form the foundation of the development of more detailed scenarios in Stage 3, whereby actual decisions can be made around funding further investigations of promising options.

7.3 STAGE 3: BRINGING IT TOGETHER: MAKING DECISIONS

KEY QUESTIONS TO ANSWER IN STAGE 3

- *What are the combinations of options—management and new investment—that best meet the development objectives of the range of stakeholders?*
- *What new investments or management measures should be taken forward for further study and/or preparation?*

Utilizing the process to make decisions: Having identified the problems to be solved and the needs of stakeholders (Stage 1), the parameters of the system and the range of specific options that could be pursued (Stage 2), the focus of Stage 3 is on how to make choices about the combinations of options that make the most sense to carry out, including complementary non-storage measures.

The focus is on examining combinations of options rather than each individual option sequentially, because it is important to understand the interactions among the current and planned forms of storage as part of hydrological, economic, and governance systems. Each potential combination could be considered a storage scenario, which can then be compared with other storage scenarios until the "best" scenario(s) for further study and potential investment are identified.

The level of detail in each scenario and the sophistication of the analytic techniques used to compare them could vary significantly. This is because each scenario is based on the data, analytic tools, and modeling capacity available to the sponsors, as well as the time and resources available. These approaches could be conceived of as existing on a continuum, such as is suggested by figure 7.2. While there are likely significant benefits to more sophisticated approaches, the important thing is to consider the full range of issues, even if only in a relatively simple or manual way.

7.3.1 Stage 3.A: Defining Scenarios

In order to compare costs and benefits of ranges of interventions at the system scale, scenarios need to be defined. A scenario is a grouping of interventions—a set of specific potential investments and management changes in a particular combination. The scenario includes specific

FIGURE 7.2 Complexity for Considering Storage Scenarios

	Simple	Complex
APPROACH	Manual comparison of most promising scenarios	Multi-objective optimization approach involving computerized simulation of multiple scenarios
DATA	Previously existing early-stage studies Professional estimates	Previously existing feasibility studies Remote sensing data
MODELING	Basic hydrological model	Multidimensional modeling, including simulation across systems, potentially linked with optimization
COST & TIME	Can be done in-house or using relatively short-term and inexpensive consulting expertise	Likely requires contracting external expertise, including sophisticated modeling capacity

Source: Original figure for this publication.

details about each potential investment's size, location, storage performance, as well as the hydrological linkages to other storage or water flows in the area of study.

The amount of detailed data available for each scenario will depend on the existence of previous studies. Where previous studies do not exist, data will need to be estimated based on techniques such as professional estimates or remote sensing. Since at this stage the purpose is to simply compare options for further investigation, very specific and detailed data—such as that needed for detailed designs— is not yet necessary.

7.3.2 Stage 3.B: Establishing Decision Criteria

Options should be evaluated against a broad set of criteria to measure the performance of the options. Regardless of the complexity of scenario modeling required, these criteria would ideally cover the technical, financial, economic, social, environmental, and governance parameters most relevant to stakeholders (box 7.4). Information to guide the development of criteria and accompanying metrics will have been collected and refined using the framework, beginning with Stage 1 with the definition of service attributes, and will continue to be useful for establishing scope of detailed studies once potential investments have been identified. Engagement of stakeholders in the selection of decision criteria is a critical component of participatory decision-making.

7.3.3 Stage 3.C: Comparing and Assessing Scenarios

How to evaluate the options and make decisions: The approach to understanding the pros and cons of each scenario—including how they might be adjusted to improve benefits and reduce costs—will vary significantly by the complexity of the need and the capacity of the entity

BOX 7.4 Storage Decision Criteria

Key considerations to define decision criteria for integrated storage planning include:

- **Technical:** Hydrological and other factors that affect the technical performance of the storage system, including volumes of water stored, levels of reliability and redundancy, physical location of storage solutions, seasonality, and interactions between different parts of the system. These factors broadly address whether a particular solution will do the job. Technical criteria need to be explicit around the nature of the service or services required and their attributes, including increasing water availability, reducing flood impact, and regulating water for other purposes.
- **Financial**: Likely financial costs, including investment costs and long-term maintenance costs, and any potential cost recovery or income that would flow from the form of storage being considered.
- **Economic**: Non-financial costs and benefits that are associated with the storage solution, such as the value of services not being charged for (e.g., public health benefits, reduced flood impacts) or the lost livelihoods associated with land-use changes. While environmental and social costs should be considered within an economic analysis, they are also broken out separately below for completeness.
- **Environmental**: Environmental impacts (gains or losses) that are associated with the storage investments (e.g., changed flows, fragmentation of river systems, increases in natural wetlands water levels, and impacts on biodiversity).
- **Social**: Impacts on people, both positive and negative, of new storage investments or different operating protocols (e.g., changes in livelihoods necessitated by new approaches to natural storage, impacts of new infrastructure, resettlement estimates). This should include an analysis of the distributional impacts of storage and possible measures for benefit sharing, as well as the potential engagement of stakeholders in the governance of new storage.
- **Governance**: Different types of storage will require different forms of governance, which may significantly impact on the likely performance and sustainability of the desired services. Consideration should be given to who will own, operate, and maintain the investment and how they will be held accountable for the performance of the investment.

Source: Original to this publication.

exploring the scenarios. There is likely a continuum of options for the overall approach to developing and comparing scenarios that could be adapted to meet the cost, time, and capacity constraints of the sponsoring institution/s. This section explores some of these approaches ranging from relatively simple to potentially cutting-edge approaches.

Less-Detailed Stakeholder-Focused Approach

Where the storage problem is relatively clear and contained, it should be possible to pursue a straightforward approach that is based primarily on local consultations, building on local experiences, and where comparisons between scenarios are done as a series of local interactions.

Local storage investments can be combined in different ways to produce different storage scenarios, which can then be compared. The different elements that could be considered are:

- **Potential investments:** Each of the potential investments is mapped and its storage service contributions estimated over time and space (service area). Different sizes, locations, and combinations of these potential investments (including associated "soft" measures such as management approaches) represent different storage scenarios for investigation.
- **Hydrological system perspective:** How these different storage nodes interact under each scenario is mapped and estimated (either manually sketched or modelled by computer) to help estimate:
  - Hydrological interactions, such as the extent to which the different investments may be additional to one another in terms of water storage or may reduce one another's performance.
  - Aggregate storage system performance compared to the previously identified needs, as well as for comparison across scenarios.
  - Potential ancillary services could also be identified.
  - Robustness to climate extremes should be estimated. For a small catchment, this may be as simple as extending previously recorded extremes by a certain percentage.
- **Financial and economic costs and benefits:** Approximate costs of each of the interventions in each scenario could be estimated based on comparable investments, local labor, and materials costs. These should include:
  - Financial costs of storage development and any potential financial returns (e.g., will any user be prepared to pay for the service?).
  - Recurrent financial costs associated with storage system management and maintenance as well as period rehabilitation and who would be responsible for these.
  - Economic costs and benefits of the investments (in other words, costs or benefits that are not directly monetized). For example, an economic cost may be the loss of productive land to a MAR zone or small dams, while an economic benefit may be the improved household health due to more reliable local water supply. (Further details are provided in box 7.5.)
- **Environmental and social impacts:** Some of these may also be captured in the economic cost-benefits, but it is important to identify and quantify these as part of the stakeholder engagement process. Issues to be identified include direct local impacts (lost land or lost livelihoods) as well as potential downstream impacts caused by reduction in or the shifting timing of downstream flows (these may be environmental, such as on downstream wetlands or fisheries, or social, such as through reduced fish catch or water available for downstream irrigation).
- **Governance requirements:** Each investment will require someone or a group of stakeholders to take responsibility for the development, operation, maintenance, and occasional rehabilitation of the storage investment. Governance arrangements need to clarify who this will be, where they obtain their authority and resources, what performance incentives they are subject to, how they will need to cooperate with others, and who holds them accountable.

The data on storage scenarios developed can be presented in simple side-by-side forms that would facilitate easy understanding and comparison by a variety of stakeholders. Table 7.4 is an illustrative example of this approach with two scenarios, but additional scenarios could be presented in this format.

Tables like this, or other simple presentations that are appropriate to the local context, could be used to facilitate community discussions about which storage scenarios

BOX 7.5 Good Practices and Resources for Economic Evaluation

Good Practices

- Understanding the distribution of costs and benefits across different stakeholders must be an essential exercise in economic evaluation of storage options—built, nature-based, or hybrid. As such, costs and benefits of all stakeholders impacted by the project must be included in the evaluation. This is especially relevant in transboundary watercourses, where interventions in one jurisdiction can have positive or adverse impacts in another.
- Systematic biases are observed in planners' estimation of potential delays, cost-overruns, and expected benefits, as well as in the study of social impacts of dams (Jeuland 2020). Analysts must be cognizant of these and attempt to identify and remove these throughout the valuation process.
- Attention must be paid to non-efficiency objectives and institutional constraints faced by planners, social and cultural evolution of attitudes of different stakeholders, as well as risk perceptions which place different weights on potential gains and losses.

Resources:

Valuation of dams and built infrastructure:

Khusro M. and B. Roy. Re-Thinking the Economic Evaluation of Water Storage. Department of Economics and the Water Institute, University of Waterloo, Ontario, Canada. (unpublished).

Whittington and Smith 2020; Jeuland 2020; Baker and Ruting 2014.

United States Federal Interagency River Basin Committee's Proposed Practices for Economic Analysis of River Basin Projects (Subcommittee on Evaluation Standards 1958).

FutureDAMS, Research Themes: Economic Analyses: Ex-post Economic Analysis of Dams. Accessed March 10, 2022. Available at: https://www.futuredams.org/research-themes/economic-analyses/ex-post-economic-analysis/.

FutureDAMS, Research Themes: Economic Analyses: CGE Economic Modelling. Accessed March 10, 2022. Available at: https://www.futuredams.org/research-themes/economic-analyses/cge-modelling/

FutureDAMS, Research Themes: Economic Analyses: Agriculture and Livelihoods. Accessed March 10, 2022. Available at: https://www.futuredams.org/research-themes/economic-analyses/agriculture-and-livelihoods/

NBS valuation:

Browder et al. 2019; Wishart et al. 2021; Kalra et al. 2014; World Bank 2019b.

For a rapid screening of costs and benefits associated with a range of green infrastructure, readers may use the Earth Economics' Green Infrastructure Benefits Valuation Tool (Earth Economics 2018) as a starting point.

InVEST (Integrated Valuation of Ecosystem Services and Trade-offs). Accessed March 10, 2022. Available at: https://naturalcapitalproject.stanford.edu/software/invest.

Lette and de Boo 2002. GI-Val is the Mersey Forest's Green Infrastructure Valuation Toolkit. Accessed March 10, 2022. Available at: https://www.merseyforest.org.uk/services/gi-val/.

would be most appropriate to meet their needs. Such an approach has the advantage of not only facilitating a decision but also increasing stakeholder ownership and therefore commitment to the next stages.

Economic Analysis of Storage Investments

Economic analysis is an important tool for policy makers deciding on the allocation of scarce public resources across competing investment needs. Ex-ante analysis evaluates the anticipated benefits and costs—tangible and intangible—of a proposed intervention, considering a with-project and without-project scenario as well as project alternatives. A well-defined counterfactual situation is important for comparing scenarios to determine the benefits and costs attributable to the intervention under consideration. Cost-benefit analysis uses market values where possible and adjusted or estimated monetary values as needed (Subcommittee on Evaluation Standards 1958). Traditional cost-benefit analysis has routinely been carried out for built storage projects and can trace its origins to water infrastructure investments (Jeuland 2020; Whittington and Smith 2020). On the other hand, the benefits of nature-based solutions (NBS) may not have market values that can be used for economic evaluation, and such analyses may rely on non-market valuation techniques such as contingent valuation (willingness to pay and willingness to accept) and revealed preference methods, which estimate values based on the actual choices that people make, such as what a family spends to travel to a scenic reservoir area for recreation.

TABLE 7.4 Illustrative Comparison of Small Catchment Storage Scenarios

	SCENARIO 1	SCENARIO 2
Storage investments	15 kilometers of terracing in X area; 3 small micro dams in locations a, b, and c; 1 km^2 MAR settlement area	10 kilometers of terracing in X area and soil regeneration in Y area. Sand dams in 2 small ephemeral rivers.
Hydrological performance	Extends growing season by 43 days in average year If 20-year drought, extends growing period by 21 days If twice as bad as previous worst drought, extends growing period by 3 days The potential for oversaturation of terraced lands during the wet season	Extends growing season by 35 days in average year If 20-year drought, extends growing period by 25 days Reduced evaporative losses by an estimated 10,000 cubic meters per year compared to surface reservoirs
Financial and economic costs and benefits	$720,000 estimated construction costs plus some voluntary community labor on terracing. Compensation to 3 families who give up a portion of their land to be inundated by the small check dams. Extended growing season estimated to increase farmer income by 15 percent, but they will have to pay $1,300 annually for O&M of new infrastructure.	$700,000 estimated construction and materials cost plus voluntary community labor for terracing and construction of sand dams. An international expert to advise on sand dams. Extended growing season estimated to increase farmer income by 12 percent. Minimal O&M for sand dams, but more time inputs required to maintain reduced tillage cropland.
Social and environmental costs and benefits	Some community members end up with reduced land holdings, but no one needs to be resettled. Small dams provide water for drinking as well as for irrigation, but downstream villages may end up with less water during the dry season. MAR settlement area provides habitat for ecologically important birds.	Crop diversification improves soil quality but reduced disturbance increases the need for pest management. No resettlement or land acquisition needed.
Governance considerations	Lack of history of paying for water in the area poses a potential challenge to the collection of tariffs needed to operate, maintain and assure the safety of the small dams.	Controls over water abstraction will need to be agreed on to avoid exhaustion of the water held in the sand dams during the dry season.

Source: Original to this publication.
Note: This table intends to introduce the estimates of additional storage associated with each option and then translating it into a service, such as additional water for crops. For instance, to estimate crop water requirements see CropWat, a decision support tool developed by the Land and Water Development Division of FAO, available at: www.fao.org/land-water/databases-and-software/cropwat/en/. O&M = operation and maintenance.

Such approaches are also used for built infrastructure projects, which also often have non-market benefits and costs associated with them.

Given the complexity of the water resources system and the broader knock-on effects of large investments such as large dams, there are two tools that offer greater understanding of proposed investments: (a) the use of hydro-economic models (HEMs), and (b) the use of computable general equilibrium (CGE) models (Jeuland 2020). HEMs integrate "*water resources systems, infrastructure, management options and economic values*" and are used to simulate behavior of the system, including its response to the addition (or removal) of storage infrastructure (Harou et al 2009; Jeuland 2020). CGE models simulate economy-wide impacts of large interventions, specifically their impacts on equilibrium prices and demand for goods and services. Both tools offer the advantage of situating the evaluation of economic costs and benefits within the context of broader system performance, which is essential to applying an integrated approach to water storage planning. However, despite the potential power of these tools for integrated planning, they are not widely used in ex-ante economic analysis of dams or other water storage investments. This is, in part, due to significant data requirements, and in the case of CGE models, the lack of market prices for water and environmental services and the need to correctly characterize water uses and their substitutability (Jeuland 2020).

While ex-ante economic analysis is used to predict how a storage project or investment will do in terms of expected benefits and costs, ex-post analysis of real-world impacts enables the derivation of conclusions about the actual performance of different storage interventions. Ex-post analysis can be done for individual investments or as systematic ("Large-N") studies using datasets covering large numbers of interventions, from which it is possible to infer causal relationships.

Other types of analysis that are highly relevant for integrated water storage planning include analysis of the distributional impacts of storage interventions, considering upstream and downstream users, as well as analysis on the cost-effectiveness and fiscal impacts of large investments being implemented with public funding.

Sophisticated Large-Area Optimization Approach

A more sophisticated modeling approach to adequately expose inter-linkages and trade-offs among different options will be required in some cases. These can include a storage gap that is severe, covers a large geographic area, and includes multiple systems beyond hydrology or multiple stakeholder groups. For example, examining storage scenarios in a large basin with multiple cities, industrial interests, agriculture, significant energy needs, as well as multiple existing storage systems is better carried out with the help of multi-criteria optimization modeling.

The modeling approach would need to:

- » Be able to create different storage facilities, along with their key parameters, as nodes within a spatially disaggregated network, and be able to model the interactions among them to derive conclusions about the overall system performance. This would include:
  - o The likely interactions of different storage nodes, including whether they are likely to provide genuinely additional storage or simply store the same water elsewhere in the system (i.e., reducing other storage—and water availability—in a similar amount).
  - o Their combined service delivery characteristics, for example, estimated contributions to increased water availability or flood protection at particular times of the year (including for particularly dry or wet years) in particular places, as well as, for example, the system's collective resilience or redundancy.
- » Incorporate the hydrological behavior of non-storage solutions, if desired, to test how non-storage investments might contribute to meeting the decision-criteria in an integrated way.

In addition to this hydrological modeling, storage scenarios would need to include estimated information about the other key types of parameters—financial, economic, environmental, social, and governance aspects.

Such modeling approaches are complex but increasingly possible due to advances in modeling approaches and cloud computing. Box 7.6 includes examples of modeling approaches that are designed to test the robustness of different combinations of infrastructure with multiple decision criteria.

Decision-Making

Multi-criteria decision-making (MCDM) (or multi-criteria analysis) techniques are widely used in water resources management for the selection of infrastructure, nature-based, and non-structural solutions to water management challenges. The typical steps involved (Yoe 2002) are similar to those employed in the problem-driven, system approach to water storage planning described in this paper, specifically:

- » Define the multi-criteria problem and objectives (Stage 1.A)
- » List and describe alternatives for meeting objectives or goals (Stage 2.B)
- » Define criteria, attributes, or performance indicators for alternatives (Stages 1.B)
- » Gather data to evaluate criteria (Stages 2.A and 2.B)
- » Arrange the alternatives against the criteria (Stages 3.A and 3.B)
- » Assign weights to criteria (Stage 3.C)
- » Rank alternatives and get results (Stage 3.C)

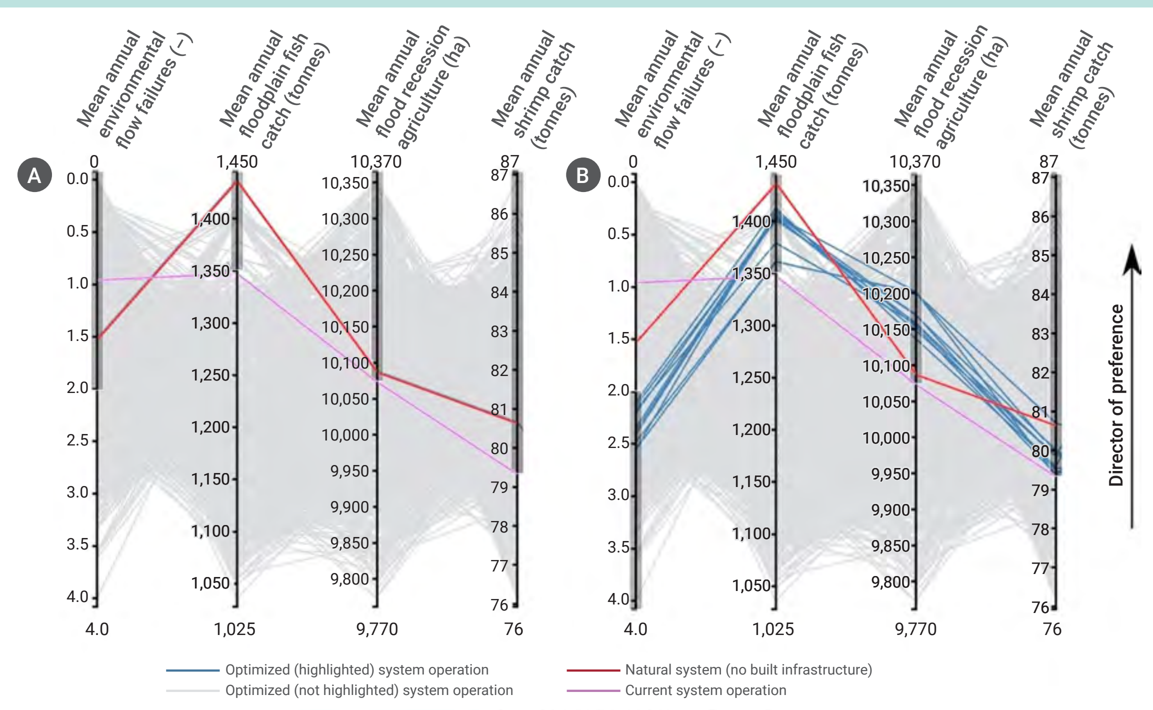
BOX 7.6 Multi-Criteria Decision-Making Using Advanced Systems Modeling and Multi-Objective Optimization

Multi-criteria decision-making (MCDM) encompasses a broad class of techniques used by decision-makers faced with competing options. They can be used to identify the most preferred option, to rank different options, to shortlist a select few, or to distinguish between acceptable and unacceptable alternatives (DCLG 2009). Unlike cost-benefit analysis, where all options are evaluated on their economic merit by converting costs and benefits into monetary streams, MCDM methods allow inclusion of a variety of criteria to reflect competing economic, ecological, and socio-cultural objectives. These criteria can further be assigned different weights using stakeholder preferences. When undertaken in a participatory setting, MCDM can empower all stakeholders with an understanding of the trade-offs involved in selecting different options.

MCDM can be used in situations where a discrete number of alternatives or an infinite continuum of them exist. They range from simple methods involving pairwise comparison of alternatives to using advancements in computational power to co-optimize up to 10 objectives at the same time. The latter allows development of multi-dimensional possibility frontiers that can be represented in simplified terms using multi-dimensional visualization techniques to enable discussion of complex trade-offs among different stakeholders.

A multi-criteria systems modeling approach is employed in the Tana River Basin in Kenya (Hurford et al. 2020) to inform how controlled releases from multiple reservoirs on the river can be optimized to maximize the services delivered through the combination of built and natural assets of the river (figure B7.6.1). These sometimes-competing services include provision

FIGURE B7.6.1 Optimized Environmental Flow Failures Against Flood-Dependent Provisioning Services



Source: Hurford et al. 2020.
Resources: Amorocho-Daza et al. 2019; Huskova et al. 2016.

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BOX 7.6 **Multi-Criteria Decision-Making Using Advanced Systems Modeling and Multi-Objective Optimization (cont.)**

of water for hydropower generation, reservoir fisheries, flood control, irrigation, and environmental reserve flows offered by the built infrastructures, as well as floodplain grazing and fisheries, riverplain gardens, beach nourishment, and marine and estuarine fisheries offered by natural infrastructure and flows to the sea. A subset of 10 performance metrics representing these services were used to define the optimization objective function.

The optimization exercise delivered Pareto optimal operating rule sets for the system—each with different trade-offs and synergies between the different services offered by the built and natural systems, among them the finding that "maintenance of environmental minimum flows traded off against the flood dependent provisioning services," leading the authors to believe that the existing regime of environmental reserve flows at discrete locations may not be suitable for protecting distributed environmental services. Meanwhile, low flow regime alteration correlated negatively with consistency of hydropower generation and positively with provisioning services.

If following the framework, the building blocks to carry out the arranging of alternatives with weighting for their comparison and ranking are laid in Stages 1 and 2.

As described in box 7.7, there are various methods for MCDM, ranging in complexity and differing in accuracy and ease of use by participants. Among the most utilized methods are pairwise comparisons, ranking methods, and weighted summation. Pairwise comparison involves listing the selected criteria, comparing them in pairs of alternatives, and indicating a preference for one alternative over another until an overall preference is revealed. Ranking typically makes use of expert opinions to inform a scale (numerical or non-numerical) based on relative performance. Weighted summation involves allocating standardized points to different criteria, assigning preference weights, and multiplying the weights by the points to arrive at a total weighted score for each alternative (Zardari et al. 2015). In water resources management and infrastructure selection, it is common for criteria to be categorized and given sub-weighting if the weighting summation method is used. For example, in its prioritization of new hydropower developments, the Royal Government of Bhutan used five categories (technical, economic, social, environmental, and balanced regional development) with a total of 21 individual criteria to arrive at a final ranking of projects (World Bank 2016c). The problem-driven, systems approach lays out potential categories of criteria to consider in Stage 3.B, utilizing comparable parameters introduced in Stage 1.B, which can be refined into appropriate criteria for the area of concern.

The selection of criteria used to compare water storage scenarios, and the weighting given to the criteria as applicable, would ideally involve stakeholders and experts who can speak to the different technical, environmental, social, economic, and governance aspects that need to be included. Depending on the nature of the storage challenge being addressed, the resources available, and the range of concerned stakeholders, the process for considering the outputs from this phase may range from a relatively simple and technocratic process to one involving significant multi-stakeholder consultations. Criteria and their weighting can come from expert input or broader stakeholder engagement, directly or indirectly, and any use must be carefully calibrated to make sure it is aiding rather than obfuscating decision-making. Expert and stakeholder preferences can be obtained directly through workshops and consultations. In addition to government agencies and local governments that are charged with leading the planning process, outside experts from the sector and representatives of beneficiary and other affected stakeholder groups may strengthen the quality of the outputs with global and local knowledge and improve the political acceptability of the ranked solutions. Criteria and weights can also be collected more indirectly through surveys or by reviewing literature and databases. Deciding on the criteria and their weights may take multiple rounds

BOX 7.7 **An Interactive Platform for Informed Decision-Making**

Planning and operating water storage systems are generally multifaceted, requiring the consideration of multiple stakeholders and needs over space and time. Novel approaches are being developed, which employ both decision-support systems and visualization, to facilitate collaborative working sessions to understand and compare trade-offs between different alternatives and scenarios, and to better help stakeholders understand each other's needs, values, and viewpoints. Finding ways to use models to inform and enable more productive stakeholder dialogue is a challenge: a promising example is the Decision Theater developed by Arizona State University (photo B7.7.1).

The Decision Theater combines a variety of sciences and technical capabilities to allow for better understanding of complex problems while enabling technical and policy decision-makers to forecast the consequences of decisions before they're made. The Decision Theater relies on a three-phased methodology: integrate models and data databases; conduct data and predictive analytics; and visualize the integrated models and data to convene engagements. The Decision Theater offers the ability to make decisions in a range of disciplines and with multiple streams of real-time information. The core physical component, called "the Drum," is a meeting space with a dashboard that provides a simultaneous view of multiple, integrated models to show how changes in one area affect outcomes in others. This dashboard allows users to toggle back and forth between the visualizations and display different models or data results based on user preferences. Economic policy, emergency preparedness, disaster response, water sustainability, and food, energy and water supply chains are some of the policy areas where the Decision Theater has been used.

PHOTO B7.7.1 Arizona State University Decision Theater

Source: Arizona State University Decision Theater website. Accessed March 10, 2022. Available at: https://dt.asu.edu/

The Decision Theater has been used to help water decision-makers to better understand how water security is affected by population growth, drought, climate change impacts, and water management policies, as well as to inform investment and policy changes around these factors. Coupled with various rainfall-runoff simulation models, the Decision Theater has encouraged viewers to manipulate assumptions and hypotheses about the future and to discuss policy options under different scenarios. It was used in Monterrey, Mexico to help stakeholders understand how the siting of upstream watershed management

(box continues next page)

BOX 7.7 **An Interactive Platform for Informed Decision-Making (cont.)**

interventions could influence downstream water flows, including flood attenuation. It has been used by decision-makers in Arizona to understand how different supply- and demand-side measures can be combined to create different water-related outcomes across different points in the system. Water decision-makers have used the Decision Theater to narrow the gap between scientific and political uncertainty by reflecting a shared understanding among researchers and decision-makers. The Decision Theater is one of many ways that modeling and visualization can be used to inform stakeholder dialogue and decision-making for water storage planning and operations.

Given the significant difficulties associated with water storage planning, new approaches to decision support systems and visualizations like the Decision Theater can help to support decision-making under a systems approach.

of discussion and may need to be done as an iterative process.

Not all MCDM approaches are equal, and different approaches have different qualities that may make one approach more appropriate than another, depending on the circumstances. Weighted summation, for example, is considered computationally simple and highly transparent if done properly, while pairwise ranking can become very complex and challenging the greater the number of alternatives being considered. One of the main criticisms of MCDM is the potential for manipulation by omission or addition of relevant criteria or alternatives, which can lead to a misplaced sense of accuracy of the results (Zardari et al. 2015).

The results of MCDM or another multi-objective optimization exercise provide a framework for decisions about which investments are worth investigating in more detail, including through detailed feasibility studies. Depending on the nature of the storage interventions (or alternatives) being considered, some of the storage options could be considered low-hanging fruit that do not require much further feasibility or other preparatory work. This may be true for relatively simple and cheap interventions that were tested within the modeling exercise to estimate unintended consequences (hydrological, environmental, social), and can therefore proceed to implementation. These might include, for example, certain landscape management approaches. However, for more significant interventions that involve greater costs, risks, and impacts, additional investigations will be required.

7.3.4 Stage 3 Outputs

A short list of potential storage options: The options assessment phase should have resulted in a short-list of potential storage options that, in combination, are most likely to meet stakeholder needs and that, based on preliminary examination, are likely to be economically, technically, socially, and environmentally feasible. Another factor to be considered is the timing of need versus timing offered by the solution—digging boreholes and withdrawing groundwater, constructing and filling up a dam, and implementing watershed management are all measures to augment supply. However, all three offer very different timelines on when the service will be delivered. In areas of acute stress, it might become more important to deliver the service.

The investment preparation phase that follows is designed to support more detailed studies that establish the feasibility of the various investments being considered, both individually, and in combination.

CASE STUDIES 8

The case studies featured in this chapter provide examples of water storage solutions that have been implemented in different parts of the world—built and natural storage types—that serve a range of different purposes across diverse geographies (table 8.1). They are not applications of the Integrated Storage Planning Framework laid out in chapters 3 and 7, but they are examples of where more integrated approaches to planning and operating water storage have been tried with success and offer lessons and insight for more holistic planning using the framework. Each case provides the relevant development and institutional context and describes the evolutionary process through which more informed decisions were made about storage investments and system operation in that particular basin or region.

TABLE 8.1 Case Study Index

	CASE	TYPE(S) OF STORAGE USED	WATER SERVICE(S) PROVIDED	WATER REQUIREMENT(S) OF STORAGE MET	5 R'S	RURAL/ URBAN
A	**Sri Lanka: Tank Cascades in the Dry Zone and the Rehabilitation of Small-Scale Water Storage**	• Small reservoirs/ retention structures	• Increased water availability • Flow regulation	• Water provision for ecosystem preservation and restoration • Water provision for domestic needs and industrial processes • Water provision to meet crop/ livestock requirements in seasons/locations without precipitation	• Rehabilitation	• Rural
B	**California: Forecast-Informed Reservoir Operation to Enhance Water Storage Efficiency**	• Large reservoirs	• Flood mitigation • Increased water availability • Flow regulation	• Prediction and attenuation of excess water for risk reduction • Water provision for ecosystem preservation and restoration • Water provision for domestic needs and industrial processes • Water provision to meet crop/ livestock requirements in seasons/locations without precipitation	• Reoperate • Reform	• Rural • Urban
C	**Cape Town: Resilience through Diversification of Water Sources and Increased Storage**	• Large reservoirs • Aquifers	• Increased water availability • Flow regulation	• Water provision for domestic needs and industrial processes • Water provision to meet crop/ livestock requirements in seasons/locations without precipitation • Water controlled for electricity generation	• Raise • Reform	• Urban

(table continues next page)

TABLE 8.1 Case Study Index (cont.)

	CASE	TYPE(S) OF STORAGE USED	WATER SERVICE(S) PROVIDED	WATER REQUIREMENT(S) OF STORAGE MET	5 R'S	RURAL/ URBAN
D	**Mexico: Green Water Storage to Adapt to Extreme Hydro-Climatic Events in Monterrey**	• Landscapes and watersheds • Soil moisture • Aquifers	• Flood mitigation • Increased water availability	• Water provision for domestic needs and industrial processes • Prediction and attenuation of excess water for risk reduction • Water provision for ecosystem preservation and restoration	• Rehabilitate • Reform	• Rural • Urban
E	**Indonesia: Getting More from Existing Built Storage: Prioritizing Rehabilitation Investments**	• Large reservoirs • Small reservoir/ retention structures	• Increased water availability • Flood mitigation • Flows regulation	• Water provision for domestic needs and industrial processes • Water provision to meet crop/ livestock requirements in seasons/locations without precipitation • Water provision to meet crop/livestock requirements throughout growing season • Water controlled for electricity generation • Prediction and attenuation of excess water for risk reduction	• Reform • Rehabilitate	• Rural • Urban
F	**Namibia: Conjunctive Surface and Groundwater Management for Drought Resilience in Windhoek**	• Aquifers • Large reservoirs	• Increased water availability	• Water provision for domestic needs and industrial processes	• Raise • Reform • Rehabilitate	• Urban
G	**Pakistan: Hydropower Development in the Jhelum-Poonch River Basin**	• Large reservoirs • Small reservoirs/ retention structures	• Flow regulation	• Water controlled for electricity generation • Water provision for ecosystem preservation and restoration	• Raise • Reform	• Rural • Urban

ANNEX 8A. SRI LANKA: TANK CASCADES IN THE DRY ZONE AND THE REHABILITATION OF SMALL-SCALE WATER STORAGE

CASE STUDY BRIEF

Summary

Small-scale water storage is a key source of resilience for rural communities in many parts of the world. This case study describes an approach to plan the rehabilitation of small-scale water storage in the dry zone of Sri Lanka, where this storage solution, locally known as tanks, has been used for centuries to harvest surface runoff and rainfall. There are more than 15,000 small tanks[1] in Sri Lanka, arranged in cascades, whereby tanks are hydrologically connected in a series. Tank cascades function as multipurpose water storage facilities for villages, providing a range of enabling services for irrigation, aquaculture, groundwater recharge, domestic drinking water use, and habitat conservation. The approach described in this case study—considering the rehabilitation of tanks within a cascade rather than as individual projects—was designed to help planners assess and understand the entire hydrology of the cascade before implementing interventions on any specific tank in the cascade. Hence, the approach helps to maximize the enabling services of each individual tank, especially to improve irrigation, while ensuring that rehabilitation of any one tank does not cause problems for other water users in the cascade or the surrounding ecology. The approach is based on multilevel participatory planning, computer simulations, and multi-criteria prioritization. The flexibility of the approach and its reliance on local knowledge mean that it can also be applied in situations where detailed hydrological databases for the tank cascade are lacking.

Type(s) of water storage used

- Small reservoirs/retention structures

Water service(s) of storage provided

- Increased water availability
- Flow regulation

Water requirement(s) of storage met

- Water provision for ecosystem preservation and restoration
- Water provision for domestic needs and industrial processes
- Water provision to meet crop/livestock requirements in seasons/locations without precipitation

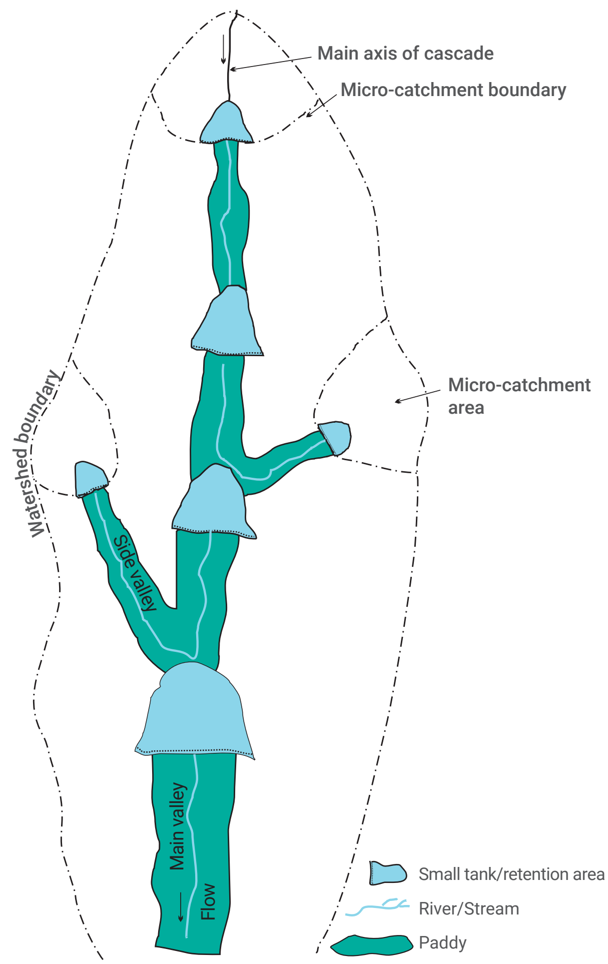
BACKGROUND

Built water storage has been critical to human settlements in Sri Lanka's dry regions for centuries. This case study describes the development and application of a system-wide approach to the rehabilitation of small water storage in Sri Lanka's dry zone. In this area, annual average evaporation (between 1,700 mm and 1,900 mm) consistently exceeds the average annual rainfall (1,250 mm), resulting in the area being water constrained. The highly variable nature of rainfall, high evaporation rates for a greater part of the year, and the low availability of groundwater mean that stable human settlements were only possible thanks to water storage. Small tanks or village tank systems have been constructed since ancient times, mostly during the medieval period, and were the centers of ancient village settlements (Panabokke, Sakthivadivel, and Weerasinghe 2002).

Small tank cascades have been a key water storage method utilized to meet water requirements. A tank cascade is a connected series of tanks organized within the meso-catchment of the dry zone landscape (Madduma Bandara 1985). It drains to a common reference point of a natural drainage course, thereby defining a sub-watershed unit with a definite watershed boundary (figure 8A.1). It stores, conveys, and utilizes water from first- or second-order ephemeral streams. In these small valleys or meso-catchments, the surface water flows are intercepted by small, constructed earthen bunds to create reservoirs that generally increase in size as one moves down the valley. Each small tank has its own catchment area. When farmers draw water from one tank to irrigate land, the irrigation return flows are captured in the next downstream tank (Madduma Bandara 1985). Nowadays there are 1,162 cascades with a total of 15,958 small tanks (Witharana 2020). Out of these, 90 percent of the cascades are located within the north, north-central, south, northwestern, and eastern provinces of Sri Lanka.

Tank cascades have been globally recognized as important agricultural heritage systems. Tank cascade systems are characterized by remarkable agrobiodiversity, traditional knowledge, and landscapes. In 2017, the Food and Agricultural Organization (FAO) designated the cascade systems of Sri Lanka as "Globally Important Agricultural Heritage Systems"; for farmers, tank cascades

FIGURE 8A.1 Cascade Water Course Schematic Diagram



Source: Based on Panabokke 2009.

make a vital contribution to both food security and livelihoods (FAO n.d.).

Small tank cascades go beyond serving agriculture and are multipurpose in function. Small tank cascades play a dominant role in supporting irrigated agriculture (primarily paddy cultivation). However, they provide enabling services well beyond irrigation. Tank cascades function as multipurpose water storage facilities for villages in rural Sri Lanka, providing enabling services such as:

» Water provision for perennial crops: Seepage water that flows laterally from the tank sidewalls and tank bed sustains perennial crops like fruit (e.g., mango, wood apple) and food trees (e.g., breadfruit, jackfruit). This also includes a variety of medicinal plants and annual food crops.

- Water provision for domestic needs: Many domestic water requirements, such as bathing, washing, and cleaning utensils, are met with water from the tanks.
- Water provision for ecosystem services: Tank cascades provide a range of ecosystem services including keeping the water table stable in nearby domestic wells.
- Water provision for fisheries: Aquaculture in tanks is an important source of animal protein.

These enabling services strengthen the resilience of rural communities against shocks. A study conducted in one of the cascades (Mahakanumulla) in the Anuradhapura District during the COVID-19 pandemic in the first half of 2020 showed that the cascade community was able to meet its food security needs despite a country-wide lockdown (Dayananda et al. 2020). This shows that the services provided by tank cascades can be an important source of resilience for rural communities.

PROBLEM DEFINITION

The enabling services that tank cascades have been providing for centuries are now threatened by several pressures. These include climate change and related floods and droughts, outdated hydro-meteorological information systems, growing socioeconomic demands, lack of watershed management, and water governance issues (MMDE 2017). The combined impacts of these pressures are (a) decreasing agricultural production due to water shortages resulting from increasing hydrological variability; (b) siltation of tanks as a result of soil erosion associated with deforestation of tank catchment areas and high-intensity rainfall events leading to reduced storage capacity; (c) decreased availability of year-round water supplies due to longer droughts and declining water quality, worsened by inadequate knowledge of seasonal weather patterns; and (d) loss and damage of livelihood assets, including livestock and community infrastructure (such as village irrigation canals), due to very heavy rainfall events and flash floods. In the floods of 2012, 982 village irrigation reservoirs and diversion canals were destroyed; 967 similar structures were destroyed during the 2014 floods (MI&WR 2018).

Farming communities and local water management institutions typically respond to these impacts by trying to augment water supplies and improve water-use efficiency. Therefore, small tank rehabilitation and improvement projects generally aim to (a) repair the distribution network to reduce conveyance losses and eventually expand irrigated areas, and (b) increase water availability by raising or extending the tank bund, or both, and by increasing direct withdrawals from streams or other tanks.

While these standard measures tend to improve water availability in the short term and around a specific tank along the cascade, they can also alter the cascade's hydrology, causing impacts upstream and downstream. Altering the hydrology of one or more tanks by increasing storage capacity, expanding the irrigated command area, or diverting water from elsewhere in the cascade changes the cascade hydrology. If the cascade has more water than demand, the effect of altering the cascade hydrology may not have significant downstream impacts. However, if water is limited in relation to total demand, there may be a serious effect on the water available to downstream users. Improvements to one tank can also affect other water users by inundating lands in the command area of the tank immediately upstream. Finally, because tank hydrology strongly influences groundwater levels, wells below tanks consistently have more groundwater than other wells, even in the driest parts of the year. Changes in water availability in tank cascades can thus affect the availability of groundwater for irrigation and other purposes. For these reasons, rehabilitation of tank cascades requires assessing and understanding the entire hydrology of the cascade before intervention to any tank in the cascade is contemplated.

While the hydrological assessment is considered key to guide rehabilitation planning, there has been no systematic attempt to collect and organize the hydrologic data on the tank cascades for any portion of Sri Lanka's dry zone. It is reported that the disappointing record of past small tank rehabilitation efforts stems from poor understanding of tank hydrology, lack of data, and the variability of water supplies in the dry zone (Sakthivadivel, Fernando, and Brewer 1997). This case study synthesizes existing methods developed in Sri Lanka to carry out a system-wide hydrological assessment of tank cascades and guide rehabilitation interventions.

INSTITUTIONAL FRAMEWORK

Rehabilitation of tank cascades has become a top priority to adapt to climate change. Sri Lanka has prepared a Strategic Action Plan for Adaptation of Irrigation and Water Resources Sector to Climate Change 2019–25 and beyond to provide adaptation actions for the sector. The recently updated Nationally Determined Contribution (NDCs) 2020–30 has identified activities to "*prioritize abandoned tanks (including small tank cascade systems) and canals to be rehabilitated in the most critical areas of climate change vulnerability, paying attention to productivity gains in restoration.*" The National Environmental Action Plan (NEAP) 2020–30 also recognizes the importance of cascade systems. The NEAP identifies ecosystem-based cascade improvement programs as a key pillar to help ensure the country's water security.

The Sri Lankan government has shown interest in maintaining the momentum of rehabilitating tank cascades. Cascade-based development was also agreed to as a national policy in 2016 (Tennakoon 2017). A major national program called "Wari Suwubagya" was initiated in 2020 to rehabilitate 5,000 small tanks within two years, though progress has not met anticipated levels. In view of this enormous task, the Department of Agrarian Development under the Ministry of Agriculture and the Irrigation Department under the Ministry of Irrigation is implementing this program with the support of the provincial irrigation departments in each province.

THE EVOLUTIONARY PROCESS: A SYSTEMS APPROACH

A four-step hydrological assessment was developed to guide the rehabilitation of tank cascades in Sri Lanka's dry zone (figure 8A.2). The assessment takes a systems approach to screen and evaluate proposals for tank cascade rehabilitation that benefit the entire cascade, rather than a single tank. This approach was initially developed specifically for small tank rehabilitation projects in the Anuradhapura District of the North Central Province in Sri Lanka (Sakthivadivel, Fernando, and Brewer 1997). The approach was subsequently refined for application in other parts of the country and with new data sources and computer models.

1. Cascade Screening

The first step consists of screening cascades using secondary data sources and field visits, followed by multilevel participatory planning and mapping of selected sites. Published topographic maps and reports provide information to identify cascades for a given area (1:50,000 topographic maps in the case of Sri Lanka). For each

FIGURE 8A.2 Rehabilitation of Tank Cascades Guide

CASCADE SCREENING	• Desk-based study of secondary sources (topographic maps) and field visits to screen cascades based on total command area and total tank and cascade surface areas • Multilevel participatory planning to further identify priorities and build a comprehensive picture of water use along the cascade
CASCADE OUTFLOW ESTIMATION	• Computer simulation to determine cascade outflow and runoff from individual tanks
CASCADE WATER SURPLUS EVALUATION	• Evaluate cascade water surplus as (WS_c) = cascade outflow per unit area (R_e)/mean annual rainfall (R_{50}). If ratio is less than 5 percent, then rehabilitation may not be hydrologically feasible
HYDROLOGICAL EVAUATION OF TANKS	• Tank water availability, as effective runoff, R_0/Irrigation requirement for Maha season (I_t) > 1 • Tank storage capacity (S_t)/Irrigation requirement for Maha season (I_t) > 0.3 • Cropping intensity in Maha season (CI_m) > 60 percent

Source: Original figure for this publication.

cascade, key measurements such as total surface area, total tank surface area boundaries, and the total command area are recorded.[2]

Field visits are carried out to further screen the cascades. The data to be collected include information on water resources, agricultural land (currently cultivated, potential for expansion), cropping patterns, seasonal cropping intensities, population details (number of farmers for each tank), tank details (number of tanks in a village, spilling details, physical condition, year of last rehabilitation), tank management (responsibility for tank management), and groundwater use (numbers of wells, water quality). For the tank cascade rehabilitation project in Sri Lanka's Anuradhapura District, this information was collected by interviewing small groups of knowledgeable farmers in each village.

Following the field visits, each cascade is scored to assess its land, water, and labor resources potential. The criteria include (a) potential beneficiary families; (b) average family holding; (c) Maha[3] season cropping intensity; (d) yields; (e) frequency of tank spilling; (f) duration of spill; (g) spill at the bottom of the cascade; (h) physical condition; (i) conjunctive use of water; (j) potential new land for development, and any other special factors. The individual items in this list correspond to key dimensions of the cascade screening as listed below (Sakthivadivel, Fernando, and Brewer 1997):

- *The greater the number of beneficiaries, the better use of investment funds*.
- *The greater the landholdings, the more each beneficiary can benefit.*
- *If yields are low due to insufficient water, the greater the potential yield gains from tank system improvements.*
- *If the tanks spill, the greater the cascade water surplus of the cascade.*
- *If the tank systems are in poor physical condition, the more they will benefit from rehabilitation.*
- *Having groundwater implies that better water supplies may help the groundwater, or vice versa.*
- *The greater the potential to irrigate new land, the greater the potential to benefit from investment*.

No single item in this scoring system is definitive; the scoring index must be considered as a whole. The higher the score, the better the cascade's potential for development. These scores can be used to further reduce the number of cascades being considered, and then guide the selection of sites for the multilevel participatory planning and mapping exercise. In the tank cascade rehabilitation project in Sri Lanka's Anuradhapura District, this initial screening was helpful to narrow down the selected cascades from 76 to 50.

For the selected cascades, multilevel participatory appraisal and planning techniques are applied to investigate and plan the rehabilitation work with farmers. This multilevel participatory planning involves getting farmers in each village to propose work needed on their tank systems and then getting representatives from all the villages together to analyze the cascade hydrology and agricultural systems as the basis for formulating development plans for the cascade. Participatory mapping is the main technique used for data analysis and planning in the case of Sri Lanka (Jinapala, Brewer, and Sakthivadivel 1996).

Farmers generally know the situations only for their own tanks and not for the cascades as a whole. By getting them together, multilevel participatory planning helps to build a comprehensive picture of water resources and water use within each cascade. This multi-village participatory planning allows farmers to consider the development of water resources in the cascade. This is important for two reasons: First, it allows farmers to make the best use of the potential water supply, and second, it avoids conflicts that might arise from improvements made without considering effects on downstream users.

The output of this exercise consists of six maps with information useful for the next steps in the process. These illustrate (a) cascade land and water resources, (b) cascade agricultural systems and land use, (c) cascade social and management institutions, roads, and other infrastructure, (d) proposed improvements to the use of land and water resources, (e) proposed improvements to agriculture, and (f) proposed changes in land and water management institutions.

2. Cascade Outflow Estimation

Once the cascades have been selected, computer simulation models are used to determine the expected outflow from each cascade.[4] The input variables for the simulation typically are (a) mean annual rainfall (government records), (b) cascade area (measured from maps),

(c) command areas of cascade tanks (measured from maps and checked by field visits and records), (d) present main (Maha) season cropping intensity (from field data collection), (e) crop evapotranspiration values (from published data and CROPWAT[5]), (f) drainage return flow coefficients (from Itakura 1994), (g) catchment runoff-rainfall relationships (from Ponrajah 1982), and (h) water application, conveyance, and distribution efficiencies, seepage, and percolation losses (average values used by the Irrigation Department). Additional input variables might include ecological flow requirements.

Key outputs from the models used are the inflows, water releases, and expected spilling from each tank. During field data collection, partially quantified estimates for these variables, particularly for tank spilling, are gathered to check the model's output and ensure that no major mistakes were made.

The importance of deriving simple relationships based on easily measurable cascade parameters, especially in contexts where detailed data and information might not be available. In the application of these models to Sri Lanka's Anuradhapura District, the simulated outflows from tanks and cascades were related to easily measurable parameters such as cascade area, tank catchment area, tank water surface area, and command area (Sakthivadivel et al. 1996; Sakthivadivel, Fernando, and Brewer 1997). The analysis indicated that the cascade outflow is directly related to cascade area, command area, and tank water surface area of the cascade and indirectly to tank storage capacities and irrigation water demand (Sakthivadivel, Fernando, and Brewer 1997). Hence, a direct way to estimate the cascade outflow from simple surface area measurements with a regression equation was developed. The analysis demonstrated that features of individual tank systems affect the cascade outflow (Sakthivadivel, Fernando, and Brewer 1997). Furthermore, it also validated the use of the simple area ratios for initial screening of the cascades.

3. Cascade Water Surplus Evaluation

The cascade outflow estimation in step 2 is followed by an evaluation of the cascade water surplus to quantify how much of the outflow is available to some or all of the tanks in the cascade. The cascade water surplus is evaluated by defining two parameters: cascade outflow per unit area and the mean annual rainfall. The cascade outflow per unit area is calculated by dividing the cascade outflow by the cascade's total area. The cascade water surplus is calculated by dividing the cascade outflow per unit area by the mean annual rainfall. For Sri Lanka's Anuradhapura District, this ratio is greater than 5 percent. This 5 percent value was estimated based on the expected runoff in a fully developed cascade under a minimum rainfall situation.

4. Hydrological Evaluation of Individual Tanks

To identify the potential of each tank in a cascade to benefit from repair and improvement, the tank must be evaluated using water resource availability, tank storage capacity, and agricultural criteria. In this case study, three indicators (tank water availability, tank storage capacity, and cropping intensity) were used to evaluate the potential of a tank system to benefit from rehabilitation investment. These indicators are quantified once the overall cascade water surplus (step 3) has been evaluated. In different settings, alternative water resource availability and agricultural criteria might be used, depending on data availability.

- Tank water availability: A cascade may be hydrologically well endowed, but the tank within it may not be so. Water supply adequacy of a tank measures the extent to which the effective runoff (R_0) to the tank is adequate to meet the irrigation requirement (I_t) in the main (Maha) season. Water supply availability is evaluated using the ratio of these two values. If $R_0/I_t > 1$, the tank has adequate water supply to meet the irrigation requirement; otherwise, additional water is needed to meet this requirement (Sakthivadivel, Fernando, and Brewer 1997).
- Tank storage capacity: The storage capacity (S_t) of a tank measures the extent to which the tank is capable of storing the runoff water and releasing it to meet the irrigation requirement (I_t). This measure is evaluated using the ratio of these two quantities. If, $S_t/I_t > 0.3$, then the tank has the capacity to hold at least 30 percent of the irrigation requirement. The value of 0.3 is arrived at based on the farmers' perception that a tank should have the capacity to hold at least five weeks of irrigation requirement before starting any irrigation operation.

- Cropping Intensity: Agricultural performance of a tank is evaluated using the average main season (Maha) cropping intensity for the past few consecutive seasons (Sakthivadivel, Fernando, and Brewer 1997). In the case of Sri Lanka's Anuradhapura District, it was concluded that a well performing cascade or tank would have a Maha season cropping intensity of 60 percent or more, based on the variability of rainfall and findings in IIMI 1996.

These indicators, together with the cascade water surplus indicator are used to guide the final evaluation of tank rehabilitation proposals and prioritize the rehabilitation of specific components of a tank cascade.

5. Evaluating Tank Rehabilitation Proposals

The four-step hydrological assessment yields a set of hydrological indicators which can be used to inform recommendations for tank system augmentation or expansion (table 8A.1). Final investment decisions on tank cascade rehabilitation also need to be based on other criteria such as costs and benefits, and consideration of other indicators of agricultural performance beyond cropping intensity, potentially including environmental sustainability, social acceptability, and economic efficiency. In Sri Lanka, the number of beneficiaries and the rehabilitation history are the two most common parameters used to decide on rehabilitation proposals. For the Anuradhapura District example, it was decided that (a) there must be at least five beneficiaries for a tank system to be considered for rehabilitation and (b) the tank system should not have been rehabilitated within the last 10 years.

SOLUTION AND IMPLEMENTATION

The four-step hydrological assessment guide helps ensure that rehabilitation of tank cascades results in greater water availability for increased cropping intensity. It also attempts to ensure that the rehabilitation of any one small-scale system does not cause problems for other water users in the cascade. The main advantage of the methodology described here is that it provides a means to rapidly assess water availability and water use without requiring the existence or the creation of a detailed hydrologic database for the cascade. Instead, farmers' knowledge of their hydrologic situations is harnessed to provide the needed data. The knowledge and data gained from well-designed rapid assessments are used to estimate flows among the separate systems within the cascade and outflows from the cascade.

Rehabilitation of small tank cascades is an investment priority to build resilience against climate change. For example, the Climate Smart Irrigated Agriculture Project financed by the World Bank and the "Strengthening the Resilience of Smallholder Farmers in the Dry Zone to Climate Variability and Extreme Events Through an Integrated Approach to Water Management" project, financed by the Green Climate Fund with Government of Sri Lanka (GOSL) co-financing have updated and

TABLE 8A.1 Recommendations on Tank System Augmentation and Expansion

	TANK SYSTEM CONDITION			
CASCADE SURPLUS	TANK WATER AVAILABILITY	TANK STORAGE CAPACITY	CROPPING INTENSITY	RECOMMENDATIONS
No	—	—	—	No expansion/augmentation
Yes	Not adequate	—	—	Tank augmentation
Yes	Adequate	Not adequate	—	Tank capacity expansion
Yes	Not adequate	Not adequate	—	Augmentation and capacity expansion (capacity expansion is recommended only if tank augmentation will be carried out)
Yes	Adequate	Adequate	High	Command area expansion (only if adequate land is available)

Source: Sakthivadivel, Fernando, and Brewer 1997.
Note: Tank augmentation entails, for example, tapping a stream to augment water supply to the tank. Tank expansion entails construction works to increase tank storage capacity. — = not applicable.

implemented this approach to guide investments in tank cascade rehabilitation in Sri Lanka's dry zone.

These investments implemented a number of innovations to the approach presented in this case study, including:

- Use of nationally determined criteria for the selection of project locations. Target areas were selected based on (a) vulnerability of communities to climate change, (b) poverty, and (c) high incidence of chronic kidney disease of unknown etiology, believed to be linked to lack of good quality drinking water.
- Hydrological assessments were typically based on more advanced simulation models, such as the Soil and Water Assessment Tool (SWAT) and Water Evaluation and Planning (WEAP) Model, which were used to model hydrological processes and water demand respectively.
- Utilization of non-hydrological criteria, including institutional and context aspects (e.g., past and ongoing interventions, rehabilitation and improvement made to the cascade during the last five years, availability of functional user organizations), social aspects (e.g., number of people or households benefitted by the cascade, poverty headcount ratio), and environmental aspects (e.g., biodiversity, area under tank bed cultivation) to prioritize interventions.
- All the tanks within the cascade, irrespective of whether such tanks have command areas and beneficiaries, are typically rehabilitated. This is because tanks without command areas capture excess runoff water, reduce the possibility of breaching the tanks below, and act as storage tanks.
- The projects designed a comprehensive stakeholder engagement program, including beneficiaries, line agency officials, and local authorities. There are grievance mechanisms in place; monitoring process have also been established.

LESSONS LEARNED

There are many lessons learned from this case study and, more broadly, from past and ongoing tank cascade rehabilitation projects in Sri Lanka (Aheeyar 2013; Tennakoon 2017; Perera et al. 2021). These lessons are relevant to places where tank cascades exist or are being considered.

- Rehabilitation of tanks using a cascade planning approach leads to more sustainable results. Compared to the ad hoc rehabilitation of individual tanks, the cascade approach presented in this case study helps planners to (a) capture any benefits arising from the joint rehabilitation of tanks in sequence, including improved sediment retention and groundwater recharge; (b) avoid conflicts between water users upstream/downstream, as unintended impacts such as flooding or shortage are avoided; and (c) improve the overall planning approach to rehabilitation through structured stakeholder engagement and project scheduling.
- Participatory planning produces key information, leads to better decisions, and creates project ownership. Tank cascade rehabilitation projects often adopt a top-down approach and disregard local knowledge and experience in the design and construction phase of projects. This case study shows the advantage of applying stakeholder engagement and participatory planning approaches in tank cascade rehabilitation projects. Stakeholder engagement helps to gather important information on the current state of tanks, on the priorities of users, and on any potential upstream/downstream issues between involved communities. Stakeholder engagement also needs to consider the line agencies involved in project development. Early orientation on tank cascade rehabilitation projects at district and divisional level helps to create ownership among responsible government officials and clarifies responsibilities and expectations. In the long term, this leads to improved decisions on tank rehabilitation as planners are better able to consider the knowledge and priorities of beneficiaries.
- Tank cascade rehabilitation programs can be linked to broader rural revitalization and connectivity programs to maximize impact. Rural development programs that address value addition, market linkages, and alternative income generation help communities in cascades to generate adequate income and reduce poverty rates. While these activities can maximize the socioeconomic benefits of agricultural production, they should be planned considering sustainable water use from the cascade.
- Adoption of the cascade approach shows that tanks without command areas often need to be rehabilitated if other tanks in the cascade are to continue

functioning. Some of the small tanks in tank cascades do not have command areas or beneficiary farmers since they were constructed for specific purposes, such as water retention and sediment retention. Through the application of the cascade approach presented in this case study, planners can decide whether these tanks need to be rehabilitated to support other tanks used for irrigation.

- Community training and mobilization are key components to ensure the success of tank cascade rehabilitation programs. Investments in tank cascade rehabilitation should be paired with targeted training programs to further strengthen farmers' knowledge of the cascade and increase access to information technology for monitoring and coordinating water use and releases along the cascade. Furthermore, continued support for farmer organizations is essential to ensure the long-term sustainability of rehabilitation, as areas without functioning farmer organizations typically experience quicker degradation of tanks.
- Ecosystem services need to be considered in cascade rehabilitation projects' economic and financial analyses. The bulk of the multiple benefits generated by tank cascades belongs to ecosystem goods and services, which are not readily assessed through traditional cost-benefit analysis. A narrowly framed economic analysis considering only on-site benefits of restoration related to increased agricultural production often cannot justify cascade-wide restoration investments. It is only when broader ecosystem services are taken into account that the economic feasibility of cascade-wide rehabilitation becomes evident.

ENDNOTES

1 In the context of Sri Lanka, a small tank is a humanmade surface water reservoir serving an irrigated area of fewer than 80 hectares.

2 Based on this information, two indicators are calculated: (1) the ratio of cascade area, Ac, to the total tank water surface area in the cascade, Acws, and (2) the ratio of cascade command area, Acca, to the total tank water surface area in the cascade, Acws. In the Sri Lanka case, for a cascade to be chosen for further consideration, the former ratio should exceed 8 and the latter ratio should be less than 2 (IIMI 1994; Sakthivadivel et al. 1996).

3 The main rainfall season, or Maha season, is from October to January when around 80 percent of the annual rainfall is received.

4 The computer simulation model is used to calculate two important parameters: (a) the cascade outflow, or the runoff volume discharging at the foot of the cascade per unit area (R_e), and (b) the effective Maha (main) season runoff (R_0) to individual tanks. R_0 is the sum of surface runoff, direct rainfall on the tank water surface, surplus water from the upstream tank, and irrigation drainage water from the immediate upstream command area minus the sum of tank evaporation and seepage and percolation losses. In the case of Sri Lanka, the Reservoir Operation Simulation Extended System (ROSES) was specifically developed by the International Irrigation Management Institute, now the International Water Management Institute (IWMI), to estimate cascade outflow.

5 Crop Water and Irrigation Requirements Program (CROPWAT) is a computer program for the calculation of crop water requirements and irrigation requirements based on soil, climate, and crop data developed by the Land and Water Division of the United Nations Food and Agriculture Organization (FAO).

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ANNEX 8B. CALIFORNIA: FORECAST-INFORMED RESERVOIR OPERATION TO ENHANCE WATER STORAGE EFFICIENCY

CASE STUDY BRIEF

Summary

Forecast-informed reservoir operation (FIRO) "*is a reservoir-operations strategy that better informs decisions to retain or release water by integrating additional flexibility in operation policies and rules with enhanced monitoring and improved weather and water forecasts*" to maximize various development objectives, potentially including water supply, hydropower production and flood attenuation (American Meteorological Society 2020). The implementation of FIRO has been piloted in Lake Mendocino, California, United States, by a partnership of water managers, engineers, regulators, and scientists from several federal, state, and local agencies, as well as universities. They have teamed up to evaluate whether current technology and scientific understanding can be utilized to improve the reliability of meeting water management objectives of Lake Mendocino, including water supply for agriculture, domestic uses, and environmental streamflow while not impairing—and potentially improving—flood protection.

Type of water storage used

- Large reservoirs

Water service(s) of storage provided

- Flood mitigation
- Increased water availability
- Flow regulation

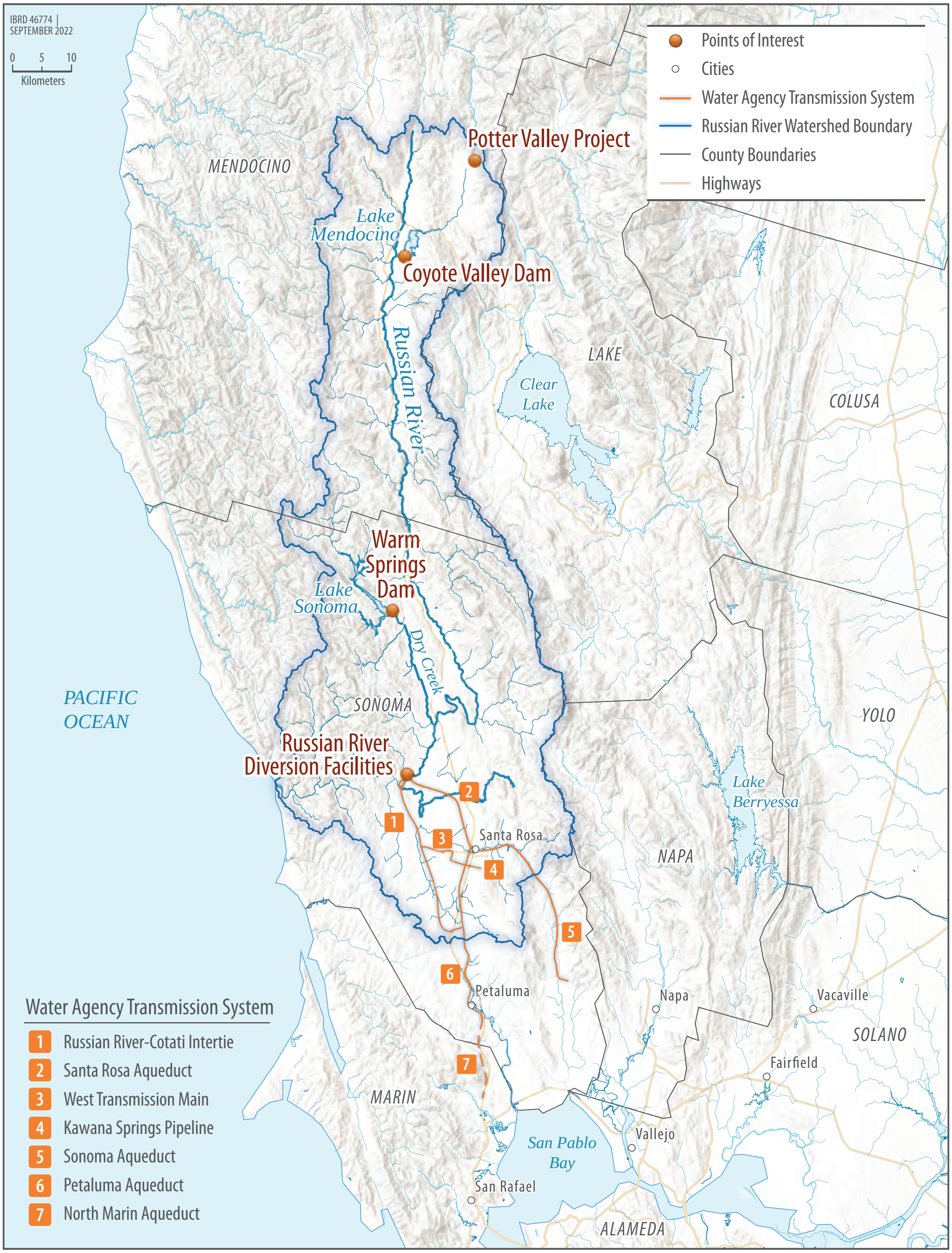
Water requirement(s) of storage met

- Prediction and attenuation of excess water for risk reduction
- Water provision for ecosystem preservation and restoration
- Water provision for domestic needs and industrial processes
- Water provision to meet crop/livestock requirements in seasons/locations without precipitation

BACKGROUND

Water resources development has been important for the Russian River watershed, located in northern California, to support economic development (map 8B.1). The Russian River is a partially managed river system with reservoir releases controlling river flows, especially throughout most of the summer and fall, to ensure water availability throughout the year. Two major reservoirs that provide water supply and flood protection are Lake

MAP 8B.1 Schematic of the Russian River Watershed and Water Transmission System



Source: Adapted from FIRO SC 2015.

Mendocino and Lake Sonoma. This water infrastructure has been supporting the economic development in the watershed, contributing to sustaining several economic activities, such as water supply for domestic uses, agriculture, hydropower, and recreation.

The multipurpose Coyote Valley Dam, which formed Lake Mendocino in the Upper Russian River watershed, also significantly contributes to environmental flows. The Coyote Valley Dam has been operated cooperatively by a local agency, Sonoma Water, and the United States Army Corps of Engineers (USACE) since 1958. Water stored in Lake Mendocino is the product of inflows from the Russian River and water transferred from the Eel River to support hydroelectric generation, via trans-basin transfer, which is released downstream to mainstream flows in the Upper Russian River. These storage releases can account for all water in the river during dry periods, protecting endangered coho salmon, Chinook salmon, threatened steelhead, and multiple other species, as well as supporting municipal and agricultural uses (CalEPA 2021). It is also critical to the region's thriving viniculture sector.

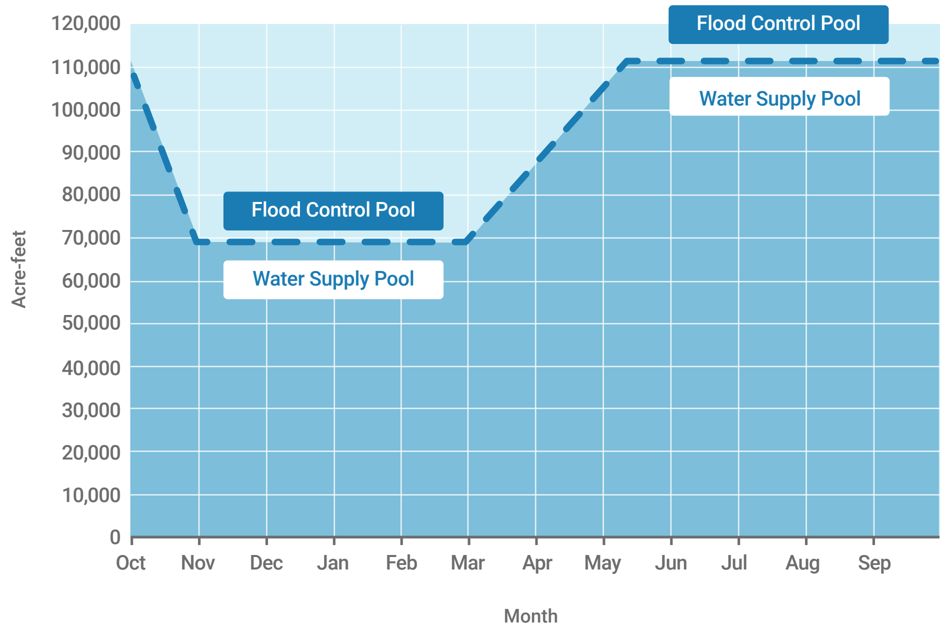
The Russian River Basin experiences one of the most variable climates in the United States, with atmospheric rivers and their extreme precipitation driving this variability (FIRO SC 2017). Average annual precipitation is as high as 80 inches in the mountainous coastal region of the watershed and 20 to 30 inches in the valleys. Precipitation can also vary significantly from season to season, which can result in a large amount of variability in flows in the Russian River, with 93 percent of annual precipitation from October to May. The climate is highly influenced by atmospheric rivers—California's version of a hurricane. Atmospheric rivers originate in the Pacific Ocean and can make landfall along the coastline, with extreme rainfall, high winds, and coastal storm surges. When these storms occur, runoff flows rapidly into valleys and coastal areas, potentially creating widespread flooding. In the Russian River, atmospheric river events often account for a large percentage of the rainfall during three or four major winter storms, and can also produce 30–50 percent of the region's annual precipitation in a few days (Ralph et al. 2013). In a warming climate, atmospheric rivers are anticipated to increase in intensity (Gershunov et al. 2019), becoming even bigger contributors to California's annual precipitation total, posing greater flood risk hazards, and complicating reservoir operations for flood control. Storms not related to atmospheric rivers, however, will contribute less to total precipitation. This means California could vacillate even more wildly between extremes of drought and flooding, requiring more space to manage the extremes. In the future, increasing demands for water will put more stress on the ability of Lake Mendocino to meet water management objectives reliably for the region, especially with more variable hydrologic conditions predicted.

The water storage in the Coyote Valley Dam fluctuates as per seasonality, and the operation of the dam is heavily governed by flood control. As a federal dam, operation of Coyote Valley Dam is governed by USACE rules—the project water control manual (WCM). Initially created in 1959 and then updated to mitigate effects on the endangered fish, those rules allocate available storage to a flood control pool at the top of the reservoir and a conservation pool (water supply pool) below that. The storage allocation strikes a balance between the need to keep an empty reservoir for managing excess flood water and a full reservoir for meeting water management objectives and environmental flows. Current rules require the flood pool to be empty except briefly in periods of greatest inflow. Then flood runoff is stored and released at a rate that avoids or minimizes the exceedance of downstream flow targets to reduce flood risks. The conservation storage, used for water management objectives and meeting minimum instream flow requirements (for fisheries and/or environmental purposes, herein referred to as environmental flows), is filled as water is available to do so (FIRO SC 2017). However, operation following the WCM rules strictly does not permit storage in the flood pool for conservation purposes. Figure 8B.1 shows the 2015 rule curve (also called the guide curve) for Lake Mendocino, with its seasonally varying storage allocation, before FIRO was introduced.

PROBLEM DEFINITION

Over time, it became apparent that Lake Mendocino was not meeting water resources and flood control needs downstream as efficiently as it could be. Releases of large amounts of water during wet seasons to make room for potential future flood attenuation were followed by dry periods; water was being released when it was not needed downstream to prepare for floods that were not coming,

FIGURE 8B.1 Simplified Lake Mendocino Guide Curve



Source: FIRO SC 2015.
Note: Water must be released from the lake between November 1 and March 1 when water levels are above 68,400 acre-feet.

and more water was needed downstream during dry periods. For example, in December 2012, a large storm associated with an atmospheric river filled space available in the conservation pool. USACE dam operators followed the WCM rules and released this water from the flood pool, ensuring space was available to manage potential future floods, even though no storms or flooding were forecast. Storage in Lake Mendocino began to decline significantly through the late winter and early spring of 2013 because no additional storm events occurred, which turned out to be the beginning of a severe and extended drought. If stored water had been retained in Lake Mendocino from the December 2012 storm and atmospheric river event, drought impacts to the Upper Russian River could have been postponed and moderated.

The current maximum allowable reservoir storage to meet flood control objectives (guide curves) for Lake Mendocino are based on hydrologic analyses at the time of dam construction and do not consider inflow variations or forecasts. Conventionally, the guide curves, a major element of the WCM, were determined to reflect average seasonal patterns and by using historical data. For Lake Mendocino, data included streamflow and weather patterns available at the time of dam construction, which was used to estimate seasonal flood potential and so defined the flood storage volume and the release requirements to keep flood storage empty in anticipation of future flood events. Since the rules do not allow the use of storage in the flood pool for other purposes, stored floodwater that could potentially be used for water management objectives has to be released to manage floods anticipated with 1950s estimates, which are based on the technology available at the time. Moreover, the guide curve of Lake Mendocino does not account for upstream flow reduction due to a reduction in the trans-basin diversion from the Eel River as a result of changes in upstream hydroelectric operations. This inflexibility of the existing operational rules has contributed to the underperformance of the dam from a water supply perspective during extreme events.

Consideration of various elements need to be included in the operation of Lake Mendocino to perform at a higher level. A more robust operation of Lake Mendocino would require the incorporation of the following aspects: natural weather variability due to the number and intensity of atmospheric river events; consideration of actual climate variability and extreme events due to climate change; and significant decreases and variability in trans-basin diversions from the Eel River into the East Fork of the Russian River. Starting in 2006, Lake Mendocino has experienced significantly reduced water supply reliability since flows were decreased from the Eel River. This provides the opportunity to assess the applicability of FIRO that incorporates streamflow predictions to adaptively manage reservoir storage to provide downstream flood risk management and limit unwanted emergency releases, while improving storage availability for water supply and ecosystems.

INSTITUTIONS AND INSTITUTIONAL FRAMEWORK

As a partner in the operation of the Coyote Valley Dam, Sonoma County Water Agency needs to follow state and federal regulations and also is entitled to water rights from the state authority. Since Coyote Valley Dam started operations, Sonoma Water has been authorized by the State Water Resources Control Board—the regulatory body for water permits and water uses in California—for the rights to appropriate Russian River water. As the local project sponsor for the construction of the Coyote Valley Dam, Sonoma Water retains rights to some of the water stored in the reservoir and controls the releases from the reservoir water supply pool. Sonoma Water is required to maintain minimum streamflows in accordance with its water rights permits (Sonoma Water n.d.). At the same time, Sonoma is required to comply with federal regulations. Since Lake Mendocino has been receiving lower annual inflows due to changes in upstream uses since 2006, the National Oceanic and Atmospheric Administration (NOAA)'s National Marine Fisheries Service has issued a biological opinion with restrictions on inflow and outflows to support the endangered and threatened salmonids in the Russian River. Sonoma Water is also required to conduct a stress test and self-certify the level of available water supplies it has, assuming three additional dry years, as well as the level of conservation necessary to assure adequate supply over that time (Water Boards 2016).

As the Coyote Valley Dam is also federally owned, its operations are governed by USACE operational policy. When federal funds are used to construct—partially or fully—a dam that includes flood mitigation as an authorized purpose, the USACE becomes responsible for managing that purpose, pursuant to Section 7 of the United States Flood Control Act, and a WCM is developed to guide water release decisions for the dam. WCMs are generally completed within a year of project completion and are updated if conditions or the physical attributes of the project change—but many WCMs have not been meaningfully updated for several decades due to a lack of USACE appropriations. When dam construction in the United States peaked in the 1960s, skill in weather and water forecasting was less advanced than present day. To reflect average seasonal runoff patterns and basin conditions, guide curves were developed using available observational hydrologic information. This information was usually derived decades ago at the time of reservoir construction and updated as conditions required (Howard 1999; Delaney et al. 2020). These procedures are codified in the WCM, and water managers are largely compelled to use them. USACE has a process where requests for temporary deviations from the existing WCM rules can be submitted, evaluated, and approved. Deviations can be either minor (5 percent or less deviation from existing guide curve levels) or major (greater than 5 percent deviation).

At the same time, there are many stakeholders for water resources management around Lake Mendocino. The Integrated Water Resources Science and Services (IWRSS) is a consortium of federal agencies with complementary missions in water science, observation, management, and prediction, such as the Federal Emergency Management Agency, NOAA, USACE, and the United States Geological Survey (USGS). The overarching objective of IWRSS is to enable and demonstrate a broad, integrative national water resources information system to serve as a reliable and authoritative means for adaptive water-related planning, preparedness, and response activities. It promotes inter-agency collaboration, such as between the National Weather Service and Sonoma County Water Agency. Under IWRSS, the Russian River Basin was selected as a demonstration area to implement pilot projects, including forecasting to improve reliability and resiliency in Lake Mendocino, enhancing monitoring capability, taking stock of hydrologic modeling and identification of gaps, and centralizing data to facilitate common data access. At the local level, the Mendocino County Russian River Flood Control & Water Conservation Improvement District is responsible for managing the water resources of the Upper Russian River for the benefit of the people and environment of Mendocino County. It is the local sponsor for the development of Coyote Valley Dam and Lake Mendocino, and monitors water levels of the lake and river flows to ensure regulatory compliance.

Alongside water resources agencies, national and local forecast and weather agencies are also important stakeholders for water resources around Lake Mendocino. NOAA's California Nevada River Forecast Center (CNRFC) provides reservoir inflow information and river flow forecasts, including the Russian River watershed. The California Department of Water Resources, and USGS California Water Science Center also provide river flow information. The California Water Data Exchange Center disseminates various water-related information and data (IWRSS and NOAA 2014). Related to atmospheric rivers, NOAA's Hydro-Meteorological Testbed (HMT) conducts research on precipitation and weather conditions and accelerates the infusion of new science and technology into daily forecasting. The HMT maintains a coastal atmospheric river observatory in the southern part of the Russian River Basin (IWRSS and NOAA 2014). At the same time, the Center for Western Weather and Water Extremes (CW3E) at the University of California—San Diego's Scripps Institution of Oceanography conducts research on atmospheric rivers, including atmospheric and soil moisture observations in the Russian River Basin and data collection over the Pacific Ocean.

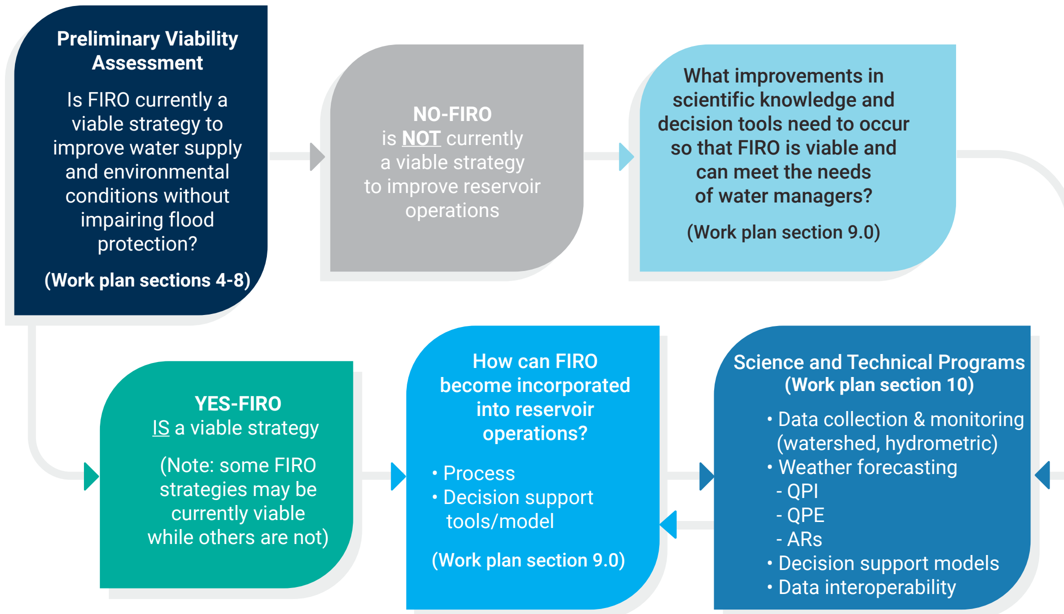
THE EVOLUTIONARY PROCESS: A SYSTEMS APPROACH

The first step toward the implementation of FIRO at Lake Mendocino involved the creation of an interagency steering committee of water managers and scientists from several federal, state, and local agencies, and universities. Participation in IWRSS activities for the Russian River demonstration area led to discussions among federal, state, local, and academic partners regarding how a new approach—building on improvements in atmospheric rivers science, and in response to a long-lasting drought—could explore the potential viability of using forecasts to inform operations at reservoirs, with Lake Mendocino as a pilot. In 2014, the Lake Mendocino FIRO Steering Committee was formed to guide the project, with an overarching role in exploring methods for better balancing flood management and the reliability of meeting water management objectives through utilizing FIRO in the Russian River watershed. The Steering Committee is co-chaired by the CW3E and the Sonoma County Water Agency, and includes USACE and other federal and state agencies, including NOAA (federal agency responsible for operational river flow forecasts across the region, regulatory perspective on enforcement related to biological opinion in the Russian River, and technical perspective on weather forecasting capability), USGS (research perspective from federal agency on scientific information for water resources management), United States Bureau of Reclamation (federal agency perspective on management, development, and protection of water resources in the West), and the California Department of Water Resources (state perspective on water resources from climatological perspective) (Talbot, Ralph, and Jasperse 2019). As such, committee membership was purposefully chosen to bring together representatives from the relevant organizations that had responsibility for operations and regulation not only at Lake Mendocino but also for conducting research into the relevant physical processes that impact water management operations, namely meteorological forecasts and hydrologic and hydraulic modeling (Talbot, Ralph, and Jasperse 2019).

The Steering Committee collaboratively developed a work plan to assess the viability of FIRO for Lake Mendocino. The first full meeting of the Lake Mendocino FIRO Steering Committee was held in December 2014, where terms of reference[1] for the committee were agreed upon. The committee agreed to meet at least quarterly, but smaller subcommittees would meet and interact more frequently as needed to ensure delivery of products of the effort. It was also determined that a work plan was needed to guide the research effort in exploring the viability of using forecast information in an operational setting. It was also recognized that the input and interaction between engineers, scientists, operators, and regulators would be crucial to the success of the development of the work plan as well as the execution of that work plan over the course of the effort. Between December 2014 and September 2015, a five-year work plan was developed, published in October 2015 (Jasperse et al. 2015). This work plan presents an approach for conducting a proof-of-concept FIRO viability assessment using Lake Mendocino as a model (figure 8B.2), including whether FIRO can support adjustments to the WCM. The work plan describes current technical and scientific capabilities and outlines technical/scientific analyses and future efforts needed to demonstrate the potential of FIRO to improve reservoir management (FIRO SC 2015).

The Lake Mendocino FIRO work plan laid out a multistep strategy to assess the viability of FIRO. The first step in the plan was to carry out a preliminary viability

FIGURE 8B.2 Flow Diagram Depicting the FIRO Viability Assessment Process



Source: Jasperse et al. 2020.

Note: QPI = quantitative precipitation information. QPE = quantitative precipitation estimator. AR = atmospheric river.

assessment (PVA), conducted over two years, to be followed by a full viability assessment (FVA), which would require substantial additional effort over roughly another three years (FIRO SC 2017):

» The PVA was an *"assessment intended to inform the [Steering Committee's] decision (1) to take steps to deploy FIRO components with existing technology; (2) to delay FIRO implementation until enhancements to the technology are available; (3) to take an incremental approach, implementing FIRO with available technology, then refining Lake Mendocino operation as enhanced technology becomes available; or (4) to seek a different solution."* Given the analysis was preliminary, *"the PVA relied on representations of FIRO system components, reasonable simulation of performance of those components, and anticipated flexibility in operation of Lake Mendocino under FIRO."*

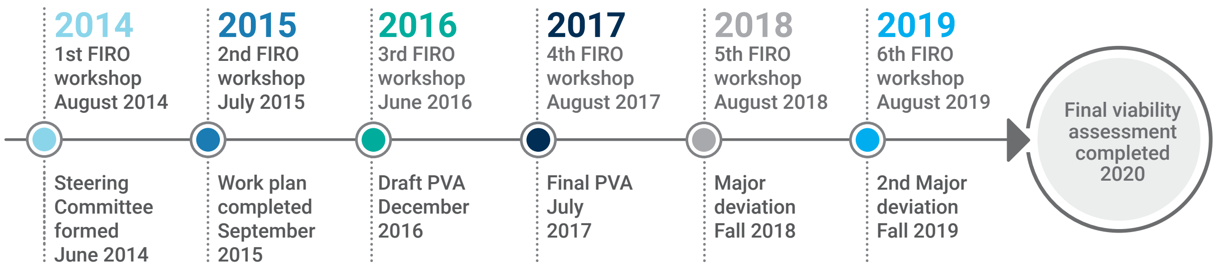
» *"In the subsequent FVA, candidate components of the Lake Mendocino FIRO system would be identified; the forecast parameters and associated forecast skill requirements would be quantified; research to improve forecast skills to meet those requirements would be conducted; alternative components formulated, assessed, and compared; and a plan for implementation developed. If the necessary components do not exist, [research and development] programs would be identified in the FVA as appropriate, and work initiated to develop the components. Finally, necessary changes to the operation rules, as defined in the project's WCM, and the process for modifying the rules would be identified in the FVA consistent with USACE procedures and protocols to support consideration of policy modifications by the USACE as it contemplates approaches to enhance reservoir operations."*

» *"If the PVA found FIRO implementation not viable, the project team would identify scientific and operational enhancements necessary to make FIRO viable. The team then would initiate a research and development effort to provide those enhancements."*

IMPLEMENTATION

Several activities were undertaken toward the assessment and piloting of FIRO for Lake Mendocino (figure 8B.3). As outlined in the work plan, deliverables included the PVA and the FVA. Annual workshops were held for connecting and sharing ideas, challenges, and results with the broader research and application communities. All the deliverables were managed by the Steering Committee and

FIGURE 8B.3 Lake Mendocino FIRO Development Pathway, 2014–20



Source: Adapted from CW3E n.d.

the workshops were organized by the Steering Committee leadership. Subsequent findings from the activities of the work plan are elaborated below.

The PVA was structured around three interconnected research questions. Each question was supported by a leading expert agency, with the objective of analyzing the feasibility of FIRO to improve operational performance of Lake Mendocino. The PVA considered the following questions (FIRO SC 2017):

A. *"If FIRO is implemented, will operations improve reliability in meeting water management objectives and the ability to meet environmental flow requirements, and if so, to what extent?"*
B. *"If FIRO is implemented, will operations adversely affect flood risk management in the system? If so, where and to what extent can that be mitigated?"*
C. *"What meteorological and hydrological forecast skill is required to enable FIRO to be implemented? Is current forecast skill for ... extreme precipitation events adequate to support FIRO, and what improvements would be needed to enable full implementation of FIRO for Lake Mendocino?"*

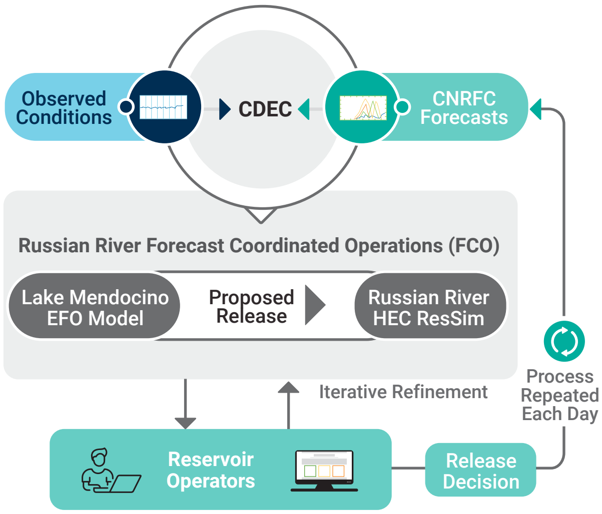
A set of analytical pieces were produced by the Sonoma County Water Agency, USACE, and CW3E to address the three questions, respectively. A final report was generated to summarize findings on FIRO alternatives, recommendations, and further work needed.

The PVA found that Lake Mendocino could be managed more efficiently by integrating reservoir inflow forecasts explicitly in release schedule decision-making. The PVA confirmed that if FIRO procedures were used, water supply benefits could be increased without adversely affecting the flood risk reduction capability. The PVA recommended several research investigations, refinement of developed procedures, the development and testing of a decision support system (DSS), and operational testing through the USACE's operational deviation process (CW3E n.d.). The USACE agreed with the finding and subsequently approved the Steering Committee's request for a major deviation from the Lake Mendocino water control plan (WCP). This temporary deviation permitted greater flexibility in managing Lake Mendocino flood control storage, pending additional investigation that would support incorporating FIRO procedures in a formal revision of the WCM. Valuable data regarding how decisions are made by the water managers at Lake Mendocino while operating under major deviations would serve to make modifications to additional major deviation requests in coming seasons until a final WCM update request is made at the conclusion of the FIRO effort at Lake Mendocino.

A DSS was developed to provide water managers with a set of tools to bring together the various pieces of data for decision-making. Data embedded in the DSS included ensemble forecasts of atmospheric river conditions from atmospheric models, CNRFC inflow forecasts, and watershed, reservoir, and downstream conditions. With all of these various pieces of data together in one place, water managers have ready access to more information upon which to make operational decisions. A schematic of how the FIRO DSS works in practice is shown in figure 8B.4. Lake Mendocino operators were trained in the use of the FIRO DSS in 2019.

The FVA shed light on the strategy to implement FIRO in Lake Mendocino. The objective of the FVA was to identify, through appropriate detailed technical analyses and other considerations, the best FIRO strategy for Lake Mendocino, along with the manner in which the strategy could be implemented in real-time operation by Sonoma

FIGURE 8B.4 FIRO Decision Support System



Source: Adapted from Talbot, Ralph, and Jasperse 2019.
Note: FIRO DSS elements and how reservoir operators can use it to inform release decisions. CDEC = California Water Data Exchange Center; CNRFC = California Nevada River Forecast Center; EFO = ensemble forecast operations; HEC = USACE Hydrologic Engineering Center; ResSim = Reservoir System Simulation.

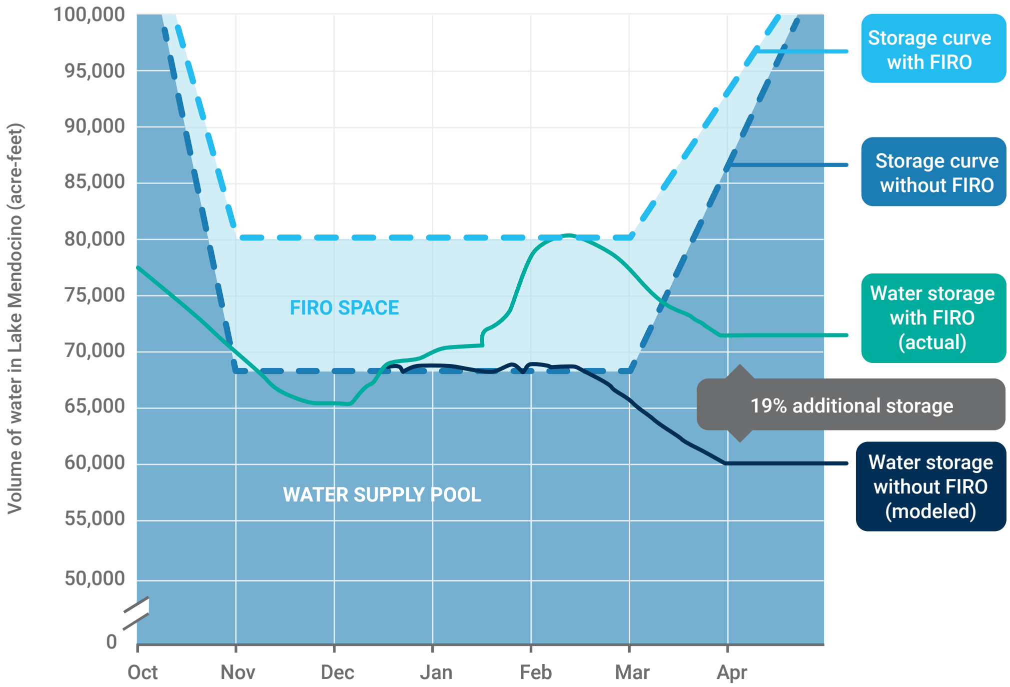
Water and USACE and enable the WCP changes necessary to implement that change permanently (FIRO SC 2019). The FVA also evaluated potential adaptive strategies that allow operators to utilize new technology and improve forecast skills as they become available in the future. The FVA was informed by collecting observational data, conducting research, modeling FIRO alternatives, and testing FIRO operations via USACE-approved major deviations from the Lake Mendocino WCM.

Operational testing was instrumental to demonstrate and test the preliminary findings identified in the PVA and better inform the FVA. The development of the ensemble forecast operations decision support tool provided an objective way to consider ensemble forecasts and manage risk associated with the inevitable uncertainty in forecasting. This led to the decision to request a planned major deviation from normal operating procedures for the reservoir based on the FIRO tools that had been developed. USACE experimented with FIRO with planned major deviations from the WCM during water years 2019 and 2020—including one winter with significant flooding in water year 2019, and one that was a drought in water year 2020. In both years, FIRO increased water supply benefits and managed flood risks, and did so in the context of two years representing opposite extremes in the weather. In 2020—the third driest year on record in the Russian River Basin—FIRO increased water storage by nearly 20 percent, roughly equivalent to the water used by 22,000 households, as illustrated in figure 8B.5.

In addition to the baseline, four FIRO alternatives were evaluated through the FVA. In line with USACE guidance, the Steering Committee prepared a hydrologic engineering management plan (HEMP) that is "*a technical outline of the hydrologic engineering studies necessary to formulate a solution to a water resources problem*" (FIRO SC 2019). The objective of the HEMP was to identify and evaluate Lake Mendocino FIRO alternatives in a systematic, defendable, repeatable manner, providing information to the Steering Committee so it may identify the best FIRO strategy. Three of the alternatives were types of ensemble forecast operations (EFO)[2] plans, and the fourth was developed by USACE Hydrologic Engineering Center (HEC) and USACE San Francisco District to leverage the five-day deterministic forecasts issued by the CNRFC and employ a simpler operation approach. To ensure direct comparison, each WCP had to meet hard (inviolable) operational constraints, as well as a set of operational considerations that could be measured. All four alternatives have various forms of flexibility in operations to allow more water storage to be carried safely into the dry season to avoid water supply shortages, and to allow reservoir levels to be lowered below the guide curve to enable additional flood protection when major storms are predicted. The FVA found that all the FIRO WCPs considered fully met the objective of a significant improvement when compared to existing WCM operations.

Analysis shows that all four FIRO alternatives would improve water supply reliability while retaining, or even enhancing, flood risk management and environmental objectives relative to baseline operations (table 8B.1). After considering all evaluation criteria, the Modified Hybrid EFO is the preferred option for near-term implementation. This option ranks favorably in terms of operational performance, can be implemented feasibly with USACE standard decision tools, explicitly uses the uncertainty in streamflow forecasts, and offers a pathway for growth with improving forecast skill and model refinements. The Steering Committee also identified EFO as an option to consider pursuing in the future, thus increasing storage capacity of Lake Mendocino.

FIGURE 8B.5 Release Curve and Modeled Release Curve, 2019–20



Source: Sonoma Water n.d.
Note: Comparison between the actual release curve with FIRO and the modeled release curve without FIRO, showing an increase of 19 percent in the water storage.

TABLE 8B.1 Water Control Plan Alternatives and Increases

ALTERNATIVE	DESCRIPTION	INCREASE IN MEDIAN STORAGE (%)
Existing operation (baseline)	Includes the seasonal guide curve and release selection rules from the 1986 USACE WCM and 2003 update to the flood control diagram.	0
EFO	Operates without a traditional guide curve and uses the 15-day ensemble streamflow forecasts to identify required flood releases.	27
Hybrid EFO	A combination of the baseline approach and the EFO. This option was used for major deviation operations in water years 2019 and 2020.	15
Modified Hybrid EFO	Identical to Hybrid EFO but with a "corner-cutting" strategy that allows for greater storage to begin February 15 to aid with spring refill. **Preferred option for near-term implementation.**	20
Five-day deterministic forecast	Defines alternative guide curves with 11,000 acre-feet encroachment space and 10,000 acre-feet draft space above and below the baseline guide curve. Uses five-day deterministic streamflow forecasts to choose the guide curve and make release decisions.	18

Source: Jasperse et al. 2020.
Note: May 10 Lake Mendocino reservoir storage over baseline water control manual (WCM) operations. Modified Hybrid ensemble forecast operations (EFO) is the Steering Committee's preferred option.

The FVA proposes a path to update and modify the WCM in an adaptive manner as conditions change. While the WCM update is a USACE process, it is recommended that the Lake Mendocino FIRO Steering Committee remain intact and contribute to the effort and process. The pathway for an updated future WCM is illustrated in figure 8B.6.

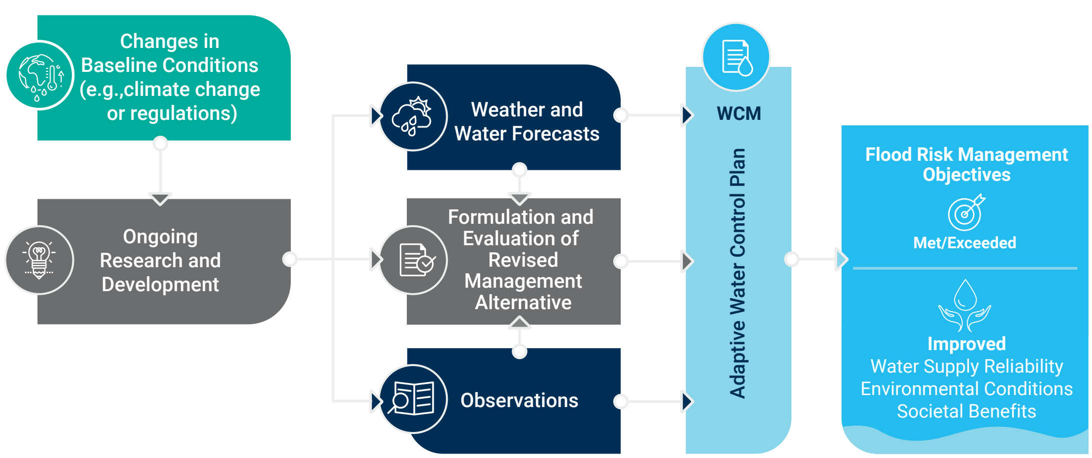
FIRO alternatives demonstrated significant benefits with limited downside. The Steering Committee conducted complementary analyses to examine the impact of FIRO on other dimensions: economic, environmental, and flood risk mitigation. An economic assessment quantified the benefits of FIRO for dam operations, water supply, fisheries, recreation, and hydropower, showing that FIRO will lead to positive benefits in all these areas except hydropower (Jasperse et al. 2020). The Modified Hybrid EFO results in total estimated annual benefits of $9.4 million. The EFO alternative has estimated total annual benefits of $9.9 million. The Steering Committee also conducted a fisheries temperature study, which concluded that EFO and Modified Hybrid EFO would offer the greatest benefits to summer rearing juvenile steelhead, while an analysis of high-flow frequency concluded that FIRO is unlikely to negatively affect Chinook salmon spawning and migration. A flood risk study found no significant difference between the baseline and the FIRO alternatives when measuring damages to structures and contents. However, when considering populations at risk, in addition to damages, all FIRO alternatives would significantly reduce risk upstream from Hacienda Bridge (near Guerneville).

The successful FVA process now opens the door to a potential WCM update. Implementation included a set of scientific and technical tasks across several disciplines, which formed the foundation for the water control plan development, and demonstrations through the PVA and through real-world testing in operations through planned major deviations. Lessons from the scientific and technical studies, plus the demonstrations (i.e., PVA and major deviations) fed into the FVA, which formally recommends the adoption of FIRO at Lake Mendocino. These steps represent the culmination of the full five-year study. However, it is important to note that they feed into the vital steps required to codify and implement the FIRO recommendations through a WCM update. This, and the five-year FIRO major deviation to be used in the meantime, are activities beyond the formal FVA laid out in the original goals and FIRO work plan in 2015.

LESSONS LEARNED

The success of the FIRO effort is due in large part to the Steering Committee, a common vision among stakeholders, and by building institutional trust among partners. The formation of the Steering Committee and the development of its internal culture of trust, cooperation, engagement, and processes successfully brought together groups with separate institutional mandates, with a common vision that a better balance between operational objectives is possible through cooperation and advances

FIGURE 8B.6 FIRO Process to Develop an Adaptive Water Control Manual



Source: Adapted from CW3E n.d.

in science and engineering. Additionally, with the connection and interaction of FIRO Steering Committee members and staff from the respective organizations that are engaged in the research and operations aspects of water management, the FIRO effort eliminated the gap that can exist between research that investigates and makes scientific advances, and operations who need tools that are ready for application to real world problems with requisite reliability and assurance. Research, operations, and regulatory perspectives have blended into the FIRO effort to produce science to inform policy and bring about improved efficiency in water management for the simultaneous benefit of flood risk management, water supply, and ecologic concerns. Expanding the FIRO community by sharing lessons learned and openly sharing and transferring tools is essential to the FIRO approach (CW3E n.d.).

FIRO represents a major policy change for USACE, contributing to the incorporation of forecast information into dam operational decision-making. In May 2016, the USACE regulation governing Water Control Management (ER 1110-2-240) was updated to include *"Forecasted conditions may be used for planning future operations, but releases should follow the water control operations plan based on observed conditions within the watershed to the extent practicable."* Thanks to the support from multiple levels of USACE, the FIRO effort contributed to defining how this could be implemented on the ground, setting an important policy application precedent for USACE and other partner agencies, and a groundbreaking experience to improve water availability without affecting water allocation.

There is an opportunity for continued improvement in FIRO at Lake Mendocino. Given the many promising leads in ongoing atmospheric rivers research and significant improvements in forecast skills that have been possible in just the past decade, there is ample reason to believe that even greater benefits may be possible with enhanced FIRO in the future. This future phase—FIRO 2.0—will be important to further improving water supply reliability and adapting to a changing climate (Jasperse et al. 2020). FIRO 2.0 will require support for enhanced observations and forecasting, modeling, and decision support tools and investing in research to improve precipitation and streamflow forecasts.

The Lake Mendocino FIRO process produced lessons that can be adapted to local circumstances. Because the Lake Mendocino FIRO effort was developed as a pilot case, the FIRO study methodology and analysis are all well documented and publicly available, forming a valuable resource base for those considering FIRO application. The multi-stakeholder process, and structured analytical process including the PVA and FVA, also yield lessons on how processes can be structured to update operating rules, and can be simplified for less complex cases, including those where flood-causing atmospheric conditions or forecasting capabilities are less advanced.

NEXT STEPS

Transferability of FIRO to other locations. USACE and CW3E are actively assessing FIRO opportunities in other settings, starting with systems dominated by atmospheric rivers. Efforts are underway to apply FIRO to Prado Dam on the Santa Ana River, New Bullards Bar Reservoir, and Lake Oroville in California, as well as the Howard Hanson Dam in Washington. These projects will yield valuable insights on the characteristics of FIRO viability for very different sites. This knowledge is being incorporated into a screening process that will help prioritize further FIRO viability assessments at other sites across the United States. The Prado Dam was selected after careful consultation with water management technical leaders, engineers, and operators within the USACE Los Angeles District, and the South Pacific Division. Additionally, the selection of a dam in this area was supported by the FIRO atmospheric science team members, based on the differences in how atmospheric rivers behave in southern California versus northern California, and on the differences in watershed characteristics that would yield new insights into FIRO potential. The Santa Ana River watershed is highly urbanized, with fast hydrological response and a large elevation difference from the upper to lower watershed, including some snow-impacted areas. An additional important difference is that direct groundwater recharge, as opposed to surface storage, is a key water management practice in this basin.

A procedure for conducting screening-level FIRO assessments will be developed and applied to additional dams in the states where atmospheric rivers affect water management operations. The criteria for selecting these dams will be similar to that used for selecting additional reservoirs for full FIRO assessments. The screening process will not be as detailed or complete as the full viability assessments for Lake Mendocino, Prado Dam, or the other full assessments. However, the screening process will provide important guidelines for how FIRO viability can be assessed at potential candidate reservoirs in the West and across the rest of the United States. This approach will systematically grow the scientific and engineering knowledge base needed to perform well-founded future assessments of FIRO applicability across a much broader range of conditions than has been explored in the first pilot reservoir, Lake Mendocino. These guidelines will assist water management agencies in deciding where and how FIRO principles and tools can be incorporated into future WCM updates (Talbot, Ralph, and Jasperse 2019).

ENDNOTES

1 The terms of reference is a non-binding agreement between the members of the Steering Committee that describes how the committee will function, make decisions, share information, and work together. This is a key element of developing an environment of transparency and trust.

2 EFO is a risk-based approach to reservoir flood operations that incorporates ensemble streamflow predictions (ESPs) made by the CNRFC (Delaney et al. 2020).

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ANNEX 8C. CAPE TOWN: RESILIENCE THROUGH DIVERSIFICATION OF WATER SOURCES AND INCREASED STORAGE

CASE STUDY BRIEF

Summary

Cape Town has depended on a regional surface water storage scheme for 95 percent of its water, shared with agriculture and other small towns. The region experienced a 1-in-590-year drought in the period 2015 to 2018, which demonstrated the city's reliance on limited water storage and on rainfall, and with little access to water from other sources. In the short term, the city was able to manage by substantially reducing water demand and taking measures to optimize water use from the regional storage system, including the transfer of water from agricultural to urban uses. Severe restrictions on agricultural water use were applied, affecting fruit production, exports, related jobs, and the gross domestic product (GDP) of the region. In response to the event, the city developed a Water Strategy with the objectives of diversifying its water sources to include reuse and desalination along with more substantial groundwater supplies, with implications for how water storage is augmented and managed. Activities to increase the resilience of the regional water storage system are underway, including an analysis of the hydro-economy, planning for optimal integration of ground and surface storage systems, removing invasive vegetation, and reviewing and updating water allocations in light of climate change and environmental commitments.

Type(s) of water storage used

- Large reservoirs
- Aquifers

Water service(s) of storage provided

- Increased water availability
- Flow regulation

Water requirement(s) of storage met

- Water provision for domestic needs and industrial processes
- Water provision to meet crop/livestock requirements in seasons/locations without precipitation
- Water controlled for electricity generation

CONTEXT

Geography, Demographics, and Economy

Cape Town is a city of approximately 4.2 million people surrounded by an agricultural hinterland with extensive wine and fruit farming served by small towns. The economy of the Western Cape is dominated by the city, which accounts for 70 percent of the province's GDP. Key industries include the financial and business services industry, manufacturing, wholesale, and trade. The region produces between 55 percent and 60 percent of South Africa's agricultural exports and contributes approximately 20 percent toward South Africa's total agricultural production (OECD 2021).

Not situated near any major rivers, the region receives most of its water from rainfall, which is quite variable throughout the year and predominantly comes in winter from cold front systems. Average precipitation for the area varies between 300 and more than 900 millimeters per year, with the higher rainfall areas in or close to the mountains, compared to an average of 495 millimeters per year for South Africa as a whole.

Water Use and the Regional Water Storage System

Cape Town is entirely dependent on the region's built water storage and distribution system to meet its water needs (photo 8C.1). The storage system is fed by surface water (96 percent) and groundwater (4 percent). The Western Cape Water Supply System (WCWSS), the primary provider of water in the region, comprises six large dams, managed as an integrated system (map 8C.1), with a combined storage of close to 900 million kl and an assured yield of 517 million m^3 per year.

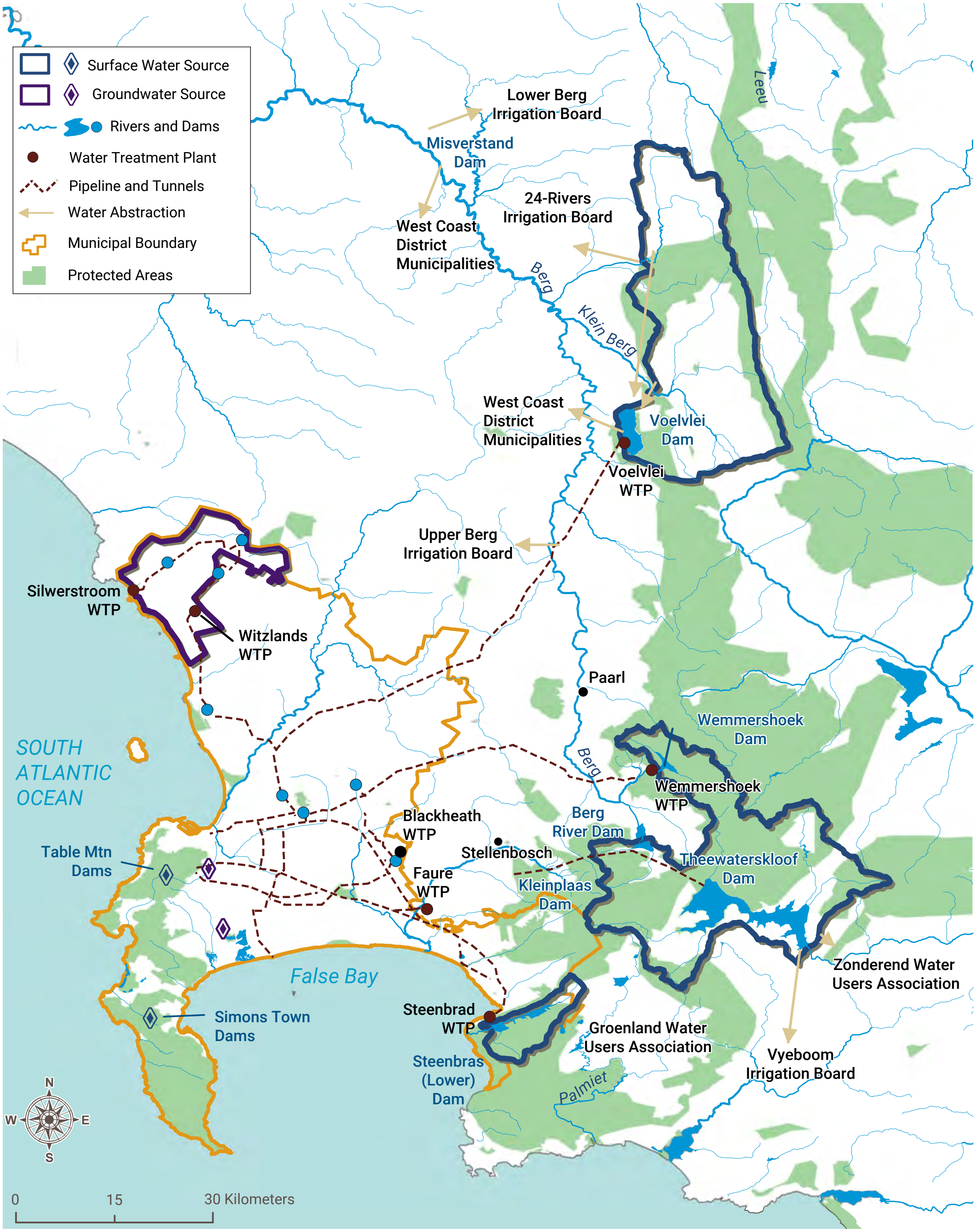
The primary purpose of the storage dams is to increase the yield and reliability of the system as a whole, and to make this water available to urban and agricultural water users. However, in recent years, there has been a reduction in the yield of the system, a significant contributor to which has been the spread of invasive vegetation, leading to potential over-allocation of the system.

Urban use: The WCWSS is primarily an urban system, with two-thirds of the yield allocated for this purpose. Cape Town relies on this system for 95 percent of its water, and its allocation from the system makes up 90 percent of the

PHOTO 8C.1 Cape Town's Reservoirs

Source: Hansueli Krapf (User Simisa [talk · contribs]), CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=13294313.

MAP 8C.1 Western Cape Water Supply System



Source: Stafford et al. 2018.

total urban allocation and 60 percent of the combined allocation for urban and agricultural use from the system.[1]

Irrigation: The other one-third of the yield is allocated to agricultural irrigation. However, not all water for irrigation in the region is provided through the WCWSS. Water for irrigation could come from a combination of sources: on farm storage, small irrigation schemes, and allocations from the WCWSS (either as direct abstraction from the storage reservoirs or as run-of-river abstraction).

Hydropower: Two pumped-storage systems are linked to the system, providing peak capacity of 580 MW, making up roughly 34 percent, 15 percent, and 2 percent of Cape Town, southwestern Cape, and national peak demand, respectively. These are operated in such a way so as to not reduce the yield of the system (box 8C.1).

Environmental services. The intention (in policy and legislation) is for the system's storage reservoirs to be operated in such a way that minimum environmental flows in the downstream rivers are protected. These flows form part of what is known as The Reserve, which enjoys priority in the allocation process set out in the legislation. The Reserve needs to be accounted for in the calculation of the system yield and taken into account in the allocation of water rights for other uses.[2]

Institutional and Governance Arrangements

Ownership: Three of the six storage reservoirs are owned by the City of Cape Town and three by national government. The six storage reservoirs are managed as an integrated system (table 8C.1).

BOX 8C.1 Hydropower Linked to the Western Cape Water Supply System

There are two hydropower pump-storage schemes linked with the WCWSS that contribute to peak demand, Steenbras (180 MW), which is owned by the City of Cape Town and directly linked to its electricity supply system, and Palmiet (400 MW), which is owned by the national electricity company, Eskom, and integrated into the national electricity grid. Peak electricity demand is about 1,700 MW for the City of Cape Town, 4,000 MW for the southwestern cape region, and 34,000 MW for South Africa as a whole.

Steenbras Pumped-Storage Hydropower Scheme

When constructed over 40 years ago, the City of Cape Town-owned 180 MW Steenbras pumped storage scheme was the first hydroelectric scheme of its kind in Africa. It has been a key source of stable electricity supply to residents of Cape Town and, in recent years, has helped avoid or minimize the impact of load-shedding on Capetonians. Each of the station's four 45 MW generator units acts as a pump-motor in one mode and a turbine-generator in the other. The peak performance of the scheme allows the city to work towards having spare generation capacity, which can help prevent load-shedding or reduce the load-shedding level for Cape Town residents (City of Cape Town 2020).

Palmiet Pump-Storage Hydropower

The Eskom-owned 400 MW pumped storage scheme is integral to the Palmiet River Government Water Scheme situated near Grabow in the Western Cape Province. The scheme has also a dual purpose similar to the Drakensberg pumped storage scheme, providing for the generation of hydro-energy between the upper 17 million m^3 Rockview Dam and lower 15 million m^3 Kogelberg Dam storages and supplementing water to nearby Steenbras Dam reservoir. From the Rockview Dam, the overspill water supplements the water supply system of Cape Town Metropolis. This is also an inter-basin water transfer scheme, developed jointly by Eskom and the Department of Water and Sanitation, and commissioned in 1988 after some five years of construction, predominantly within the Kogelberg Nature Reserve. The Palmiet pumped storage scheme was awarded the 2003 Blue Planet Prize from the International Hydropower Association for its contribution to sustainable development and good practice in utilizing hydropower resources (Barta 2017).

TABLE 8C.1 Summary, Yields, and Allocations of Dams Supplying the WCWSS, 2019

DAM NAME	OWNERSHIP (year[a])	CAPACITY million m^3	YIELD PA million m^3	ALLOCATIONS (urban)	ALLOCATIONS (irrigation)	BALANCE million m^3
Theewaterskloof	DWS (1978)	**480**	184	99	179	**-56**
Run-of-river (Berg)			38			
Voëlvlei	DWS (1971)	**164**	99	94	14	**-9**
Berg River	DWS (2009)	**130**	82	80	10	**-2**
Wemmershoek	CCT (1957)	**59**	52	54	0	**-2**
Steenbras Lower	CCT (1921)	**33**	43	63	0	0
Steenbras Upper	CCT (1977)	**32**				
Transfer (Palmiet)			20			
Total		**898**	**517**	**390**	**203**	**-76**
System integration (returns to system)			30			- 46

Source: DWS 2019.
Note: CCT = City of Cape Town; DWS = Department of Water and Sanitation; PA = per annum.
[a] Year commissioned.

Allocation of use rights: In terms of South Africa's constitution, water resources management is primarily the responsibility of national government,[3] and water use rights are granted by the national Department of Water and Sanitation.[4] Water allocations from the system are based on a calculation of a yield at a defined level of assurance of supply, taking into account The Reserve (see "Environmental services" in the preceding section). The yields are based on stochastic modeling of a synthetic probabilistic distribution of forecast inflows, derived from historical hydrological records. The yield for urban water use is based on a 98 percent assurance of supply, and the agriculture water use allocation is based on a 95 percent assurance of supply. The implications of this system are that irrigated agriculture is expected to manage more frequent, but milder, restrictions and, for urban areas, less frequent, but more severe, restrictions.

System modeling and monitoring: The national Department of Water and Sanitation is responsible for maintaining an up-to-date hydrological model of the system, to run this model annually to inform decision-making, and to monitor (and report on) rainfall, dam inflows, dam levels, and abstractions from the system.

System augmentation: A thorough study was undertaken in 2007 of the demand and supply balance in the system, and recommendations were provided on options to maintain a balance between demand and supply over the medium and long term in the context of growing urban demand (DWA 2007).

Participatory governance: A steering committee chaired by the national Department of Water and Sanitation, that comprises all major WCWSS stakeholders, was established in 2007. The purpose of this committee was to oversee the implementation of the recommendations from the Reconciliation Strategy (to maintain a balance in demand and supply over the medium and long term) and to make recommendations on interventions to maintain balance in the system in the short term (next hydrological year), based on the annual update of the hydrological model.

Decisions to restrict abstractions: During periods of low rainfall, the Steering Committee would be informed of, and respond to, recommendations on the level of restrictions to be applied based on defined operating rules for the system. The actual restriction decision is made by the national minister responsible for water, and the decision is published in the official government gazette.

Decisions to augment supply through additional storage or other interventions: The intention was for an annual

System Status Update to be produced by the National Department of Water and Sanitation.[5] This report would inform the Steering Committee on progress with the implementation of interventions to maintain a balance between demand and supply over the medium and long term. The Steering Committee was not a decision-making body. Augmentation decisions needed to be made by the national Department of Water and Sanitation (as custodian of the national unitary water resource) in conjunction with the City of Cape Town (as a major user in the system), and other users.

Transparency: Transparency in the above system was facilitated by making all reports and meeting minutes available on a website dedicated to the WCWSS Reconciliation Strategy.[6]

Catchment management: The Breede-Gouritz Catchment Agency undertakes catchment management functions for part of the area of the WCWSS.[7] The rest of the area is managed by the national Department of Water and Sanitation. The national policy intention is for the establishment of wall-to-wall catchment management agencies.[8]

A MAJOR DROUGHT WITH SERIOUS ECONOMIC CONSEQUENCES

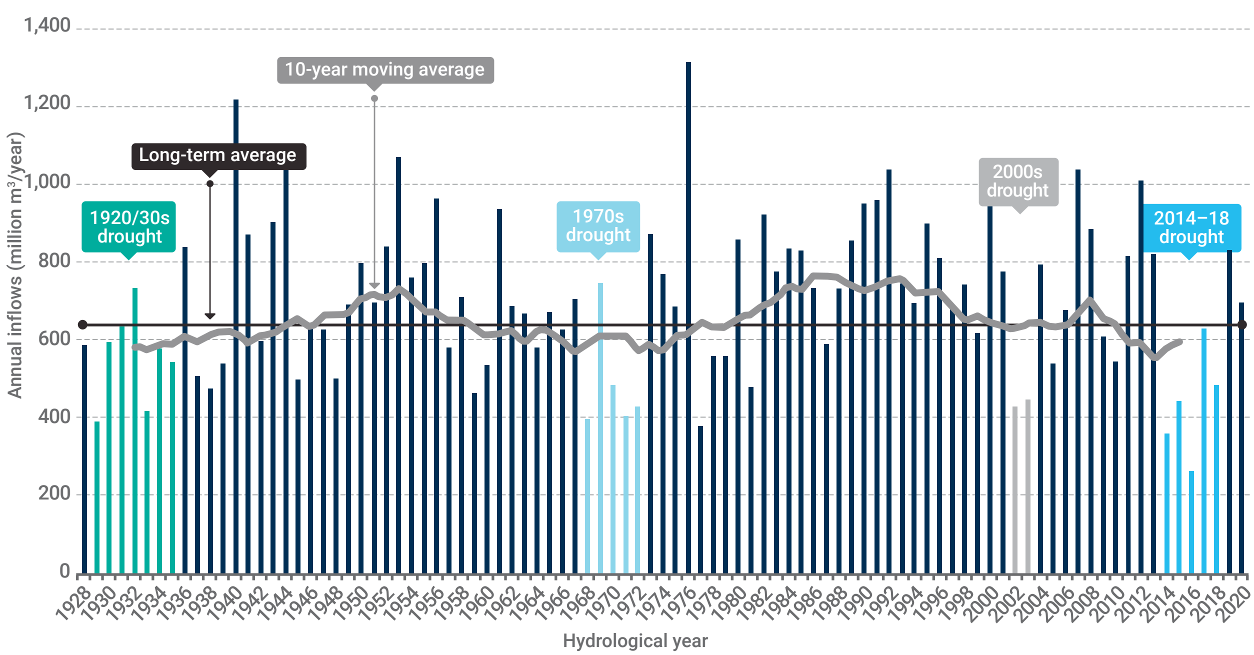
Cape Town and its environs experienced four successive years of low rainfall from 2015 to 2018 (figure 8C.1). Based on historic hydrological records available at the time, this was considered to be a 1-in-590-year hydrological event (City of Cape Town 2019).

Aggregate reservoir storage levels in the WCWSS dropped precipitously from overflowing in the winter of 2014 to just 20 percent at the end of summer in 2017 (figure 8C.2).

Severe restrictions were imposed on both agriculture and urban water users. In the case of urban users, the restrictions were to avert what would become known internationally as "Day Zero" and to prevent dams from becoming empty.

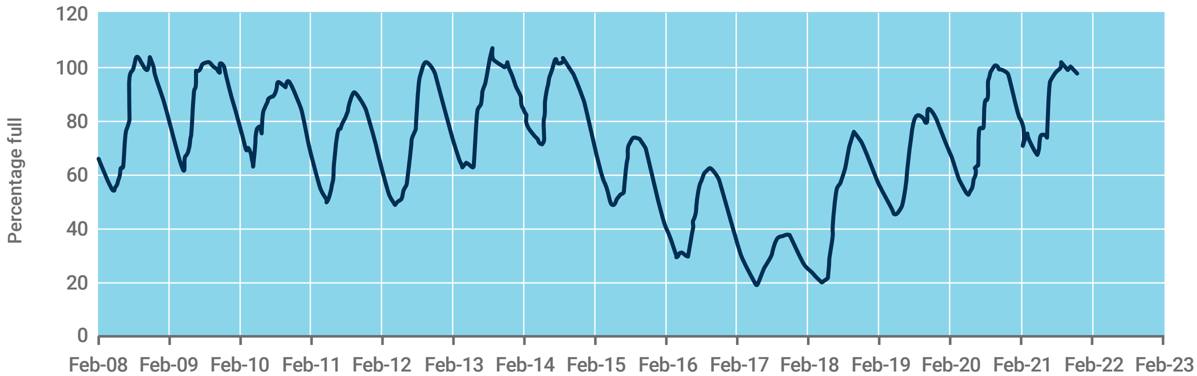
The economic costs of the crisis have been estimated to be in the region of $1 billion to $1.5 billion as a result of reduced agricultural output, tourism, and investment, and associated job losses of approximately 37,000, among others (Pegasys 2021).

FIGURE 8C.1 Annual Inflows into the Large Water Supply Dams, Cape Town, 1928–2020



Source: City of Cape Town 2022.
Note: Hydrological years start on November 1 of the prior year.

FIGURE 8C.2 Aggregate Dam Levels in WCWSS, Cape Town, 2008–22



Source: City of Cape Town 2022.

BUILDING WATER RESILIENCE FOR THE MEDIUM AND LONG TERM

Getting through the drought itself primarily focused on reducing water use while supply augmentation and additional storage are part of the longer-term strategy for resilience. In response to the drought, water use went from summer peak season water use of 1,200 million liters per day before the drought (December 2014) to a low of 500 million liters per day during the height of the crisis (February 2018), saving 700 million liters per day (figure 8C.3). And while demand management is a critical part of water management, especially in areas prone to drought, looking at alternate water supply sources and additional water storage, rather than depending solely on rainfall and built water storage, became a necessity for Cape Town.

After weathering the 2014–18 drought, the next step was to evaluate actions to carry out in the medium and long term that would help mitigate the impact of future droughts in the region. The use of built water storage for nearly all Cape Town's needs has been the case for the last 125 years, with the first dam for water supply constructed in 1896, and this has served the city well, up until recently.

But the circumstances around which Cape Town must navigate in terms of its water security have changed. Economic and population growth in the Cape Town metropolitan area is rising significantly, and even with increased demand management measures in place, there is a corresponding rise in water demand—though this increase is still lower than it was prior to the last drought. Rainfall is becoming less predictable in the face of climate change,

FIGURE 8C.3 Cape Town Gross Water Use, 2011–21

Source: City of Cape Town 2022.

meaning less water is available for storage, but the potential capacity of surface water storage has reached its upper limit, as suitable sites for additional dams are scarce, unavailable, or insufficient to meet the rising demand. Ultimately, the system is too dependent on one water source (rainfall) to fill all the dams and meet the water demand needs of the city. It needs to diversify its water risk and sources, while expanding overall storage capacity.

Prior to the 2014–18 drought, Cape Town's system for planning, implementing, and managing the regional water storage system was reasonably advanced and robust by international standards (Muller 2018). More than a decade ago, sophisticated long-term planning was based on climate and hydrological monitoring and forecasting (Muller 2018); multiple interventions were evaluated and ranked (DWA 2007); a system of water rights was put in place; and a multi-stakeholder governance arrangement with transparent processes had been established to oversee interventions to maintain a balanced system in both the short and long term. Why, then, were the impacts of the drought so much more severe than had been planned for, exposing weaknesses in the system that needed to be addressed? Efforts to address both are discussed below.

Planning and Security of Water Rights in the Context of Climate Change

The onset of the drought occurred after three years of spilling reservoirs. In fact, the storage reservoirs had spilled toward the end of winter in five of the seven years in the period 2008 to 2014. While a number of activities were underway to augment supplies, there was not a sense of urgency and even, perhaps, a level of complacency. As a result of effective demand management from the previous drought in 2000, Cape Town was well within its allocated assured supply at the onset of the drought in 2015. In retrospect, Cape Town did not have adequate water storage.

Additional allocations from the integrated storage system had also been made to agriculture but the calculated system yields were not updated at the time. Revised yields, based on up-to-date hydrological records, showed that the system was actually over-allocated (table 8C.1) and therefore the water use rights "on paper" were not secure in practice.[9] A group of scientists concluded, based on historical data on rainfall and reservoir inflows, that climate change led to a threefold increase in the likelihood of the 2015 to 2017 drought (Otto et al. 2018; Ziervogel 2019).

Three lessons arise from these facts:

Updating models. The importance of regularly updating hydrological and forecasting models as well as operating rules of the system is heightened in the context of climate change. Integrated storage systems can result in a sense of complacency, with stakeholders acting as if the system were able to reliably deliver water in most instances, making users unaware and unprepared for extreme shortages.

Scenario-based planning. Stochastic models based on historic hydrological records are insufficient. While the models used before the onset of the drought did factor in climate change, these models assumed a gradual change over time and did not adequately account for the possibility of step changes in climate (and hence dam inflows). In its new Water Strategy (City of Cape Town 2019), Cape Town has explicitly adopted a scenario planning approach, taking the possibility of a step-change in rainfall into account.

Updating and revising water rights. Water allocations (and associated water rights) from the integrated system need to be regularly updated to ensure that these rights fall within the available yield for a given assurance of supply. In the absence of this, the system will be less secure and the impacts of droughts more severe.

Diversification of Sources and Storage Types

The overdependence on the WCWSS integrated storage system means that Cape Town is particularly vulnerable to multiyear droughts and hence climate change.[10] However, few opportunities exist to build further traditional water storage reservoirs, dependent on runoff from rain, in the region.[11] Therefore, the growth in urban water demand (as the population and the economy grow) will need to be met largely from a combination of increasing water use efficiency (including addressing nonrevenue water) and the exploitation of diverse sources of water, including water reuse, desalination, removal of invasive vegetation, and further developing groundwater sources and stores.

Cape Town has developed and is implementing a plan to add 300 million liters per day of new capacity from diverse sources over the period to 2030 (figure 8C.4).[12] Of this additional capacity, less than 15 percent is from new surface water storage. As this system evolves, new approaches to managing the entire system will be needed to optimize cost and system operation and ensure resilience.[13] This is particularly important given the fact that the costs of reuse and desalination are substantially higher than water from traditional surface water storage systems.

Two lessons arise in this context:

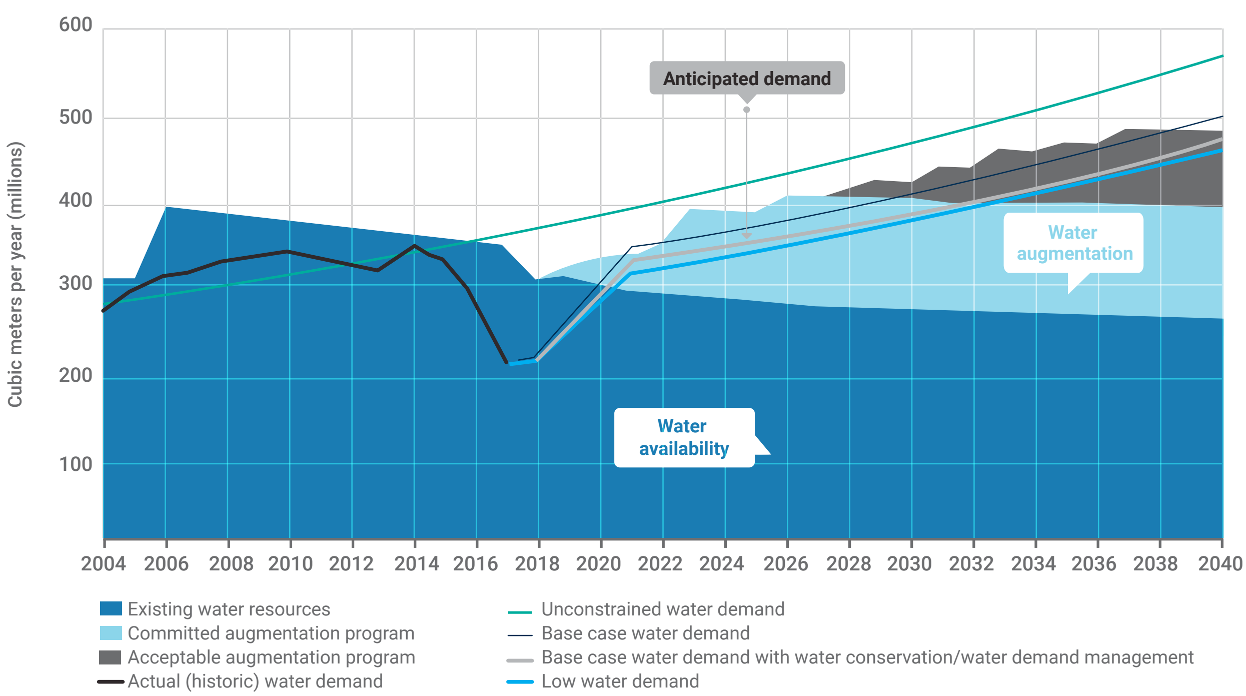
Resilience through diversification. Greater resilience can be achieved through the diversification of sources, rather than an overdependence on one water source. This helps to build flexibility and redundancy into the supply system, increasing security of supply in context of climate change risks. This will require sophisticated systems design, including storage, and greater technical capacity to both implement and manage these systems. Cape Town's new Water Strategy (2019) indicates a move in this direction (figure 8C.5).

Balancing resilience and costs. More resilient systems will be more costly to build and maintain because of the need to make greater use of more expensive sources of water. However, in countries such as South Africa, resources are scarce, which, in some provinces, makes options such as wastewater reuse less expensive than buying bulk water. The challenge is therefore to find an appropriate balance between resilience and costs, that is, "enough resilience" at an "affordable" cost. While this is partly a technical design issue, the tradeoff is likely to be more art than science. This means that the technical staff involved in system design must also appreciate the role of communication and trust-building in getting political buy-in for the required investments, allowing elected representatives to make informed choices related to the spending of public money (and any commercial financing) and in the approval of the necessary associated tariffs.

Opportunities from Aquifer Storage Potential

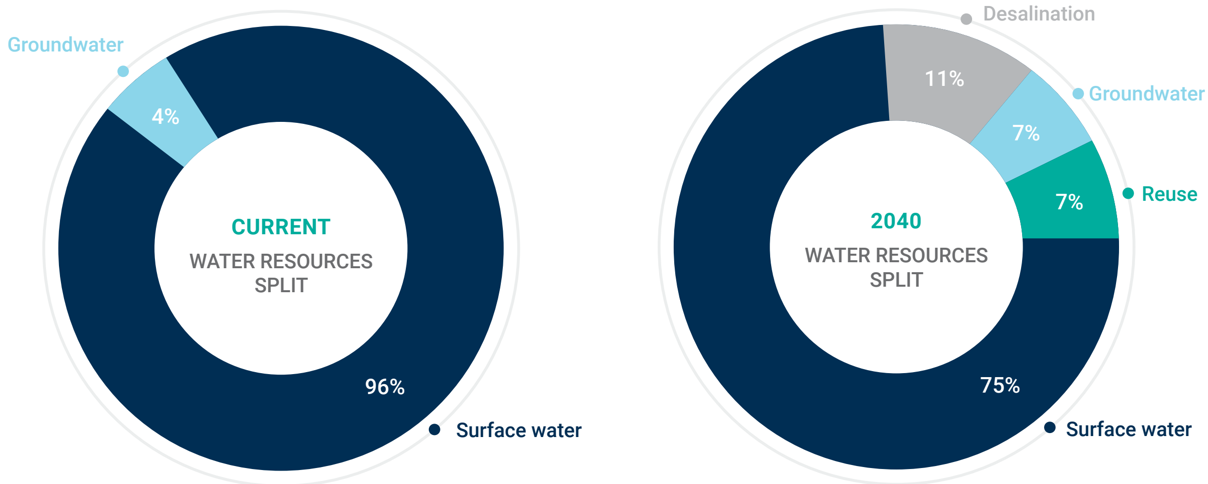
The Cape Flats aquifer provides several opportunities to strengthen the water security of Cape Town as a new source of water supply and storage facility, enabling water reuse and storage of desalinated water. The Cape

FIGURE 8C.4 Water Availability, Anticipated Demand, and the Augmentation Program, Cape Town, 2004–40



Source: City of Cape Town 2020b.

FIGURE 8C.5 Cape Town's Plans to Diversify Water Sources



Source: City of Cape Town 2019.

Flats Aquifer is large: over 400 km^2 in extent with a depth of between 15 and 40 meters. Annual rainfall over the aquifer equates to 200 million kl per year, representing close to 40 percent of the yield of the integrated surface water storage system.[14] Total aquifer storage could be of the order of 800 million kl,[15] almost as significant as the total surface water storage in the regional system of close to 900 million kl. The City of Cape Town is developing an aquifer recharge and recovery scheme for the Cape Flat and aims to abstract 50 million liters per day (18 million kl per year), which is within the sustainable yield of the aquifer and meets the terms of a water use license granted by the national Department of Water and Sanitation (Mauck and Winter 2021). Cape Town already operates a 20 million liters per day managed aquifer recharge and recovery scheme that supplies the satellite town of Atlantis, in the northern part of the metropolitan area. This scheme is primarily used for water recycling. It was developed in 1979 and rehabilitated and expanded in 2017, during the height of the drought (Walton 2017).

Cape Town's Water Strategy commits the city to transitioning to a water sensitive city. Integrated use of Cape Flats Aquifer, together with stormwater and wastewater, forms part of this transition. While there appears to be considerably more potential to make use of the aquifer as a storage amenity, a number of complex factors need to be considered including water quality, the height of the water table (which is very shallow in many areas), flood risks, saltwater intrusion, and geographic distribution of good abstraction and recharge sites, among others.

Environmental Services

Negative storage. Studies have shown that the spread of certain invasive non-indigenous species in the catchments reduces runoff into storage reservoirs and hence the yield of the system. This could be considered "negative storage." Interventions to address this through ongoing programs to clear alien invasive species are a low-cost method of increasing system yield (or preventing yield from declining) and have been prioritized in the Cape Town Water Strategy.

Protecting estuaries. The National Water Act of 1998 prioritizes an allocation of water, called The Reserve, to provide for a basic supply of water for human needs and to protect rivers and estuaries. In the latter case, the purpose is to preserve minimum flows during the dry summer months. The system of water rights authorizations needs to take The Reserve into account as a priority.

Strengthening Institutional and Governance Mechanisms

The significant stress placed on the system exposed weaknesses in the institutional and governance mechanisms described in "Context" earlier. Cape Town's Water

Strategy commits the city to work with other stakeholders to strengthen the resilience of the regional water system.

Improving the information base and building trust. The effective functioning of the system depends on trust across institutions and between major stakeholders. Both irrigators and urban citizens were unhappy with the sacrifices asked of them. A robust governance system is needed to manage these tensions and to support difficult decision-making and implementation. A hydro-economic study was completed in 2022 to improve stakeholder knowledge of the system, how it works, and the trade-offs needing to be managed going forward as demand increases and more expensive supplies are introduced into the system. A highly consultative process is being followed with a key objective of building understanding and trust across the system.

Strengthening the licensing process. South African water policy must juggle the triple goals of equity (including redress), economic efficiency (make best use of a scarce resource to support economic growth) and environmental sustainability. Proposed policy changes in 2013 prioritized equity, and new allocations were made in this light.[16] However this, together with the explicit inclusion of The Reserve requirement, resulted in the system being over-allocated, exacerbating the impact of the drought. Farmworkers, among the least advantaged in society, were negatively affected through loss of jobs and income. Licensing processes need to be robust and disciplined, only (re)allocating water that is available.

A role for water transfers. The transfer of stored water between irrigated agriculture and urban users played a small but important role during the crisis, underscoring the importance of water rights and institutional arrangements around storage. There has been some uncertainty regarding the trade of water in South Africa. At the time, government policy was against the transfer of rights; however, the courts have subsequently affirmed the right to transfer water in defined circumstances.[17]

A more robust system. Full dams in the years prior to the drought had possibly led to a sense of complacency in the overall management of the system. Restrictions had been applied late, there was uncertainty as to the accuracy of the operational modeling results, licenses had been allocated that exceeded the system yield, the hydrology had not been updated, canals had been allowed to become silted, and some pumps were in disrepair. A robust system requires a clear set of policies, rules, and procedures that are effectively implemented.

Improving institutional capacity and governance. The capacity to undertake the actual operations of the WCWSS sits within the national Department of Water and the City of Cape Town, and governance of the system is through a multi-stakeholder committee. The existing catchment management agency, which covers only part of the areas of the WCWSS, plays a limited role. Options for improving institutional capacity and governance of the system were explored as part of the hydro-economic study. One proposal put forward and under consideration is to establish a single catchment management agency that coincides with the WCWSS, and for the system to be governed under the umbrella of the catchment management agency. Another option would be to delegate the operations and management of the system to the City of Cape Town, which would need to be able to do longer-term financial planning than it currently does due to the constraints of planning and financial cycles of municipal government.

Maintaining political support for investments in water security. It is harder to maintain support for the necessary investments in infrastructure to secure water security into the future when the dams are full. The technical experts involved in the planning and management of the system need to be able to communicate effectively with the political leadership to get and sustain their support for the investments and associated tariffs that are both necessary to finance these investments.

LESSONS LEARNED

Planning and Water Rights

- Update hydrological and planning models regularly and explicitly incorporate climate change into models;
- Adopt planning methods that properly incorporate climatic and non-climatic risks; and
- Regularly review and update water rights.

A Changing Role for Storage

- Don't over-rely on water storage. Diversify sources and build flexibility and redundancy into the supply system, increasing security of supply in context of climate change risks (system design/technical), as well as drought preparation plans. Storage can imbue a false sense of security, resulting in over-reliance on the storage system;

» Understand resilience-cost trade-offs and make informed decisions;
» Use aquifers as an integrated part of water storage system (system design/technical);
» Develop approaches that optimize the integration of expensive water into the system (system design/technical);
» Understand the role of "negative storage" and mitigate effects; and
» Protect minimum river flows in the allocation process and how the system is managed.

Strengthening Institutional and Governance Mechanisms

» Improve information base and build trust across stakeholders;
» Strengthen the licensing process;
» Make use of water transfers;
» Build more robust systems through clear policies, rules, and operating procedures;
» Locate functions where there is institutional capacity (or build institutional capacity) and strengthen governance through clearer and stronger accountability mechanisms; and
» Maintain political support for investments in water security even when the dams are full through good communications and stakeholder engagement (political/leadership).

CONCLUDING SUMMARY

Cape Town and its surrounding areas depend almost 100 percent on built water storage for their water supply, 96 percent of which comes from a regional surface water storage scheme fed by rainfall. The region experienced a 1-in-590-year low drought in the period 2015–18. The city responded by developing a new Water Strategy, acknowledging that due to population and economic growth, increased rainfall variability, and the limited potential for additional surface water storage, Cape Town needed to diversify its water supply beyond a built storage system that relies solely on rainfall. The Strategy includes the objectives of decreasing its dependence on the built water storage system that is dependent on rainfall, through developing water reuse and desalination as well as substantially increasing groundwater use and storage, with implications for how water storage is augmented and managed. Activities to increase the resilience of the regional water storage system are underway, including an analysis of the hydro-economy, planning for optimal integration of expensive sources with ground and surface storage, and reviewing and updating water allocations in light of climate change and environmental commitments.

It is not possible to build yourself out of a drought. Although relatively good governance and institutional systems were already in place, the severe drought exposed several weaknesses that are now being addressed. A key challenge is to win the necessary political support for institution-building and investments that will provide security into the future and to obtain approvals for the tariffs that are necessary to finance these investments, especially as the reductions in water demand have had the unintended consequence of generating less revenue for the city. Sound governance systems, with accountability and transparency, are a critical foundation for building water security.

ENDNOTES

1 Cape Town gets the remainder of its water from some small local dams on the top of Table Mountain, springs, and groundwater.
2 The difference between policy (theory) and practice is discussed later in the case study.
3 South Africa is a constitutional republic with three spheres of government: national, provincial, and local, each with elected representatives, powers, and functions derived from the constitution and funded by a combination of a legislatively-guaranteed share of national income together with allowed revenue-raising powers.
4 Water use rights could be in the form of a general authorization, an existing lawful use or a water use license. See www.dws.gov.za/ewulaas/WUA.aspx.
5 See, for example, DWS (2019).
6 See www.dws.gov.za/iwrp/RS_WC_WSS/default.aspx.
7 www.breedegouritz.co.za.
8 Hydrological years start on November 1 of the prior year.
9 Water rights allocations exceed the available yield by 9 percent (table 8C.1).

[10] The ratio of storage to system yield is 1.64. This means that, without any rainfall and any reduction in allocations, the dams would empty in less than 20 months. This ratio is much lower than in many urban systems. For example, the ratio for the storage system supplying Sydney, Australia, is 4.8, so that the dams can provide 57 months of supply. Sydney's sustainable supply is 540 million kl per year and dam storage 2,582 million kl (NSW 2021).

[11] These opportunities are identified in the 2007 reconciliation strategy (DWA 2007).

[12] This is set out in the City's Water Strategy (City of Cape Town 2020).

[13] A study, supported by National Treasury and implemented through the World Bank, is currently underway to understand the economic trade-offs between urban and agricultural water use and implications of different options for managing the augmented supplies vis-a-is the existing system.

[14] Average annual rainfall over the aquifer is a little more than 500 millimeters (Gintamo, Mengistu, and Kanyerere 2021). Not all of the rainfall will result in aquifer recharge, but the aquifer is also recharged from stormwater outside of the area as well as treated wastewater.

[15] Assuming an average water column depth of 2 meters.

[16] "Decision-making in reallocation of water will have equity as the primary consideration" (DWS 2013).

[17] Updated policy positions (DWS 2013); Lötter NO and Others v Minister of Water and Sanitation and Others (725/2020) [2021]; ZASCA 159 (November 8, 2021).

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ANNEX 8D. MEXICO: GREEN WATER STORAGE TO ADAPT TO EXTREME HYDRO-CLIMATIC EVENTS IN MONTERREY

CASE STUDY BRIEF

Summary

This case study demonstrates the application of a multi-stakeholder planning approach supported by quantitative decision analysis to identify green water storage solutions for a rapidly urbanizing area in Mexico, the Monterrey Metropolitan Area (MMA). Ensuring that the hydrological services provided by these areas are well maintained and preserved is crucial to maintaining the city's water security. Following a sequence of floods and droughts between 2010 and 2013, multiple efforts were initiated by national authorities, the private sector, and civil society to respond to the metropolitan area's water security challenges. As part of these efforts, the MMA Water Fund (FAMM, for its acronym in Spanish, *Fondo de Agua Metropolitano de Monterrey*) was set up by a multi-stakeholder consortium to maximize the environmental services provided by the San Juan River Basin, in particular its capacity to regulate water flows, provide water supply, and reduce erosion.

Since its inception in 2013, the activities of the FAMM provide a valuable case study on a systems approach to identify green storage solutions to secure water supplies and reduce flood risks in urban areas. In particular, the case study focuses on two aspects of the FAMM's experience: First, the multi-stakeholder planning processes and champions, which provided an institutional and science-based platform to guide the FAMM's activities; and second, the application of multistep watershed conservation planning process to quantify opportunities for ecosystems to store water and regulate its flows. As Monterrey continues to grapple with the prospect of Day Zero and as policy makers consider options to enhance the city's water security, the systematic approach to planning and identifying green storage solutions described in this case study becomes even more relevant.

Type(s) of water storage used

- Landscapes and watersheds
- Soil moisture
- Aquifers

Water service(s) of storage provided

- Flood mitigation
- Increased water availability

Water requirement(s) of storage met

- Water provision for domestic needs and industrial processes
- Prediction and attenuation of excess water for risk reduction
- Water provision for ecosystem preservation and restoration

BACKGROUND

Monterrey, Mexico, is one of Latin America's economic centers and industrial capitals. The MMA, anchored by the City of Monterrey, is the second largest and most productive area in Mexico, with an estimated population of 5.3 million people, and a gross domestic product of $140 billion. Monterrey is northern Mexico's commercial center and is home to many national and international corporations.

Monterrey is prone to intense floods and droughts—threats that are likely to increase because of climate change. Rainfall is scant and highly variable, with mean annual precipitation of approximately 600 millimeters. Most rainfall is seen in September, with dry periods from January to March and November to December. This high intra-annual freshwater variability is exacerbated by high inter-annual variability, which results in intense droughts and floods. The 2011–13 drought caused major drops in the city's reservoirs and led to intense pressure on the MMA's water supplies. Rural water users bore the brunt of the impact: The drought damaged over 50,000 hectares of crops and killed more than 10,000 livestock. The 2011–13 drought was preceded by extraordinary rainfall events linked to Hurricane Alex, which caused widespread flooding and destruction in 2010, costing some $1.35 billion.

High freshwater variability alone cannot be blamed for these impacts. Monterrey was founded in the 16th century in a flood-prone area along the Santa Catarina River, part of the San Juan River Basin. The city's vulnerability to hydroclimatic hazards (floods and droughts) has increased over time due to poor land management, expansion of urban areas, and a limited water supply portfolio.

To confront freshwater variability, Monterrey has long invested in gray water storage solutions. There are three main reservoirs that make up 60 to 70 percent of the MMA's current supply. First, La Boca Dam, constructed in 1936 just upstream from where the Río San Juan meets the Río Bravo, with 829,900,000 m^3 active capacity, and second, the Cerro Prieto Dam, which was built in the early 1980s in the adjacent Río San Fernando watershed to supply the MMA with domestic and industrial water (Cháidez 2011). It was the first case of inter-basin transfer of freshwater to cope with water shortages in Mexico's northeast. Finally, El Cuchillo Dam, located 75 kilometers upstream to La Boca Dam, began operations in 1993 primarily to supply water to Monterrey and involved the reallocation of water from irrigators to domestic users (Aguilar-Barajas and Garrick 2019). A new reservoir (Presa Libertad) is currently under construction. The 2021–22 drought highlights that Monterrey remains highly vulnerable to hydro-climatic extremes and climate change, further motivating the need to identify and implement a range of storage solutions.

PROBLEM DEFINITION

The catastrophic floods and droughts of the early 2010s provided a strong rationale and motivation for the city to pursue the systems planning approach described here. In this case, climate extremes provided openings to foster collective action and pursue evidence-based investments in solutions for water storage and ecosystem conservation. Building upon the recognition that crisis fostered action, the case study explains how green water storage solutions were adopted to achieve two key development objectives: reducing the impacts of flood-related disasters and strengthening resilience and maintaining access to safe and affordable drinking water.

Reduce the Impacts of Flood-Related Disasters and Strengthen Resilience

While the MMA receives less than 600 mm of rain per year on average, intense rainfall events occur every three to four years. When these extreme events occur, often associated with tropical cyclones, the city, and the San Juan River Basin where it is located, receive as much as 100 mm of rainfall within a 24-hour period. These downpours result in flash floods, which often overwhelm the city's storm drainage system and can cause the Santa Catarina River to overflow its banks (Aguilar-Barajas and Garrik 2019). Some of the worst flood-related disasters are linked to hurricanes, which generate large amounts of precipitation over critical areas of the San Juan River Basin, causing the Santa Catarina River to swell and flood the city, as observed in 1988 during Hurricane Gilbert and in 2010 during Hurricane Alex. In the sparsely populated upper reaches of the San Juan River Basin, flood events are also associated with significant erosion and some landslides (in part due to deforestation), which result in a great accumulation of sediments downstream in the city and in water quality degradation. Therefore, a comprehensive approach to reduce flood risks needs to take a basin-wide perspective, integrating the sub-basins of the San Juan River Basin upstream of the city where most of the flash floods are generated.

Access to Safe and Affordable Drinking Water

Approximately 60 percent of Monterrey's drinking water supply comes from upstream areas in the San Juan River Basin that have been degraded from land-use change, forest fires, industrial pollution, and invasive species. Degradation has led to erosion, changes in run-off, and decreasing water quality. Industrial expansion, urban growth, and agricultural development have also led to over-extraction from groundwater and surface water reservoirs. Areas that have not been degraded equally necessitate protection and conservation actions to ensure they continue to provide hydrological services. Like gray infrastructure, green infrastructure also needs maintenance to continue providing safe and affordable drinking water. Furthermore, the city's expansion has meant that water use has increased at a much faster rate than water supply. From 2000 to 2013, water use in the MMA grew by around 45 percent, while water supply only increased by 12 percent (Magaña et al. 2021). All these factors combined mean that the reliability and quality of water services for drinking and other purposes are under threat, requiring a basin-wide approach connecting the city to its water sources.

INSTITUTIONS AND INSTITUTIONAL FRAMEWORK

The main institutions involved in the case study are:

» **Servicios de Agua y Drenaje de Monterrey (SADM):** Under the government of the state of Nuevo León, SADM is an autonomous public water and sewer utility that both supplies water in the MMA and is the water authority throughout the MMA.
» **The National Water Commission (CONAGUA):** An administrative, technical advisory commission within Mexico's Ministry of the Environment and Natural Resources, CONAGUA administers national waters, manages, and controls the country's hydrological system, and promotes social development.
» **The Nature Conservancy (TNC):** a global environmental nonprofit that advances environmental conservation through conservation projects, extensive collaboration and partnerships, and developing and analyzing best-available conservation science to guide action and measure results.
» **A range of private sector actors,** including FEMSA, a Monterrey-based multinational operating in the beverage and retail sectors.
» **International financial institutions:** Inter-American Development Bank (IDB) and the Global Environment Facility (GEF) as partners.

Following the catastrophic flood of 2010 and drought of 2011–13, TNC convened these stakeholders to discuss options to advance the city's water security. Out of these stakeholder engagement processes, the FAMM was established in 2013. The FAMM was established by a multi-stakeholder consortium to maximize the environmental services provided by the San Juan River Basin, in particular its capacity to regulate water flows. This initiative was initially spearheaded by TNC, IDB, the FEMSA Foundation, and the GEF, and rapidly included more than 40 partners, including the federal government through CONAGUA, local government, non-governmental organizations, civil society groups, and universities.

The FAMM was established building upon the lessons and experiences of water funds in other parts of Latin America. Water funds are an Investment in Watershed Services (IWS) mechanism program, whereby individuals and organizations are compensated using different methods for protecting watersheds. The payers in an IWS program are the water users that rely on the services of the watershed, for example, water utilities and industries. Large water users who depend on the continuation of service for their business can make contributions that will preserve the basin (Calderon 2013). FAMM's establishment and subsequent conservation activities were also supported through grants from charitable foundations or international financial institutions.

The objectives of the FAMM are to reduce flooding, improve infiltration, and create environmental awareness among the public. At the time of its creation, the FAMM contemplated a range of solutions to achieve its objectives. These included a combination of green and gray infrastructure, such as reforestation, firebreaks, erosion barriers, fencing, retaining walls, runoff traps, check-dams, earth dikes, and large-scale urban rainwater harvesting areas, along with public awareness campaigns. Following its initial success and the development of the watershed conservation plan, in 2016 the FAMM changed its name to Monterrey Metropolitan Environment Fund (retaining the same acronym FAMM) to expand its remit to broader environmental conservation issues beyond water.

THE EVOLUTIONARY PROCESS: A SYSTEMS APPROACH

To help guide FAMM'S activities, TNC developed a watershed conservation plan to identify where and what to prioritize to achieve its objectives (reduce flooding and erosion, improve infiltration, and create environmental awareness among the public). This section of the case study is based on the detailed technical report underlying the conservation plan (Hesselbach et al. 2019).

The development of the watershed conservation plan was led by TNC in collaboration with local and international experts. The plan focused on identifying solutions to reduce flood risk and erosion in selected areas of the San Juan River Basin. The basin is responsible for producing Monterrey's water supply, and it is also the major source of riverine flood risk for the city. The watershed conservation plan was guided by four overarching questions:

A. What is the watershed's runoff control capacity, and how does this capacity change under alternative conservation scenarios?
B. What are the threats and pressures?
C. By how much does vegetation cover reduce rainfall-induced erosion, and how is this phenomenon related to runoff?
D. How can green and gray infrastructure be combined to achieve the plan's objective?

To address these questions, the plan followed a four-step approach that resulted in two key outputs: (a) a GIS-based tool for suitability mapping and guiding the selection of target areas and (b) a watershed conservation plan, which includes maps of priority areas for green water storage solutions. Stakeholder engagement was included through the four steps. The engagement targeted the small number of people living in the area of maximum impact (see step 1 below) and the City of Monterrey, where the conservation plan was discussed with the institutions identified in the section above. Stakeholder engagement was centered on (a) explaining the plan's focus on ecosystem services and the functioning of the water fund; (b) identifying the major water-related threats (step 2) and (c) discussing the type and feasibility of the interventions (steps 3 and 4).

The four-step approach to the plan included:

Step 1: Identification of the area of maximum impact

Limited resources were available to address Monterrey's water problems; therefore, the evolutionary processes began with the identification of a priority area to be targeted by the plan. This priority area is called area of maximum impact (AMI). It was identified based on two criteria: (a) contribution to the metropolitan's area water supplies and (b) level of biological and ecosystem diversity and connectivity. Existing studies of the city's water supplies and hydrological time series data were used to rank the upper sub-basins based on their contribution to surface water flows and aquifer recharge, upon which the city's water supplies depend. The sub-basins were then overlaid onto a map of key biodiversity areas (most important places for species and habitats) to identify areas with potential to generate benefits in terms of hydrological services and biodiversity conservation. Based on this assessment, a large part of the San Juan River Basin was identified as the AMI. This area is responsible for generating about 70 percent of the city's water supplies and also contains six protected areas, including two major areas (Cerro de la Silla, Cumbres de Monterrey).

Step 2: Identification of threats

A stakeholder workshop was used to identify threats to the AMI´s hydrological and ecological services. Stakeholders were also asked to rank threats according to their severity, coverage, reversibility, and frequency, following the scoring matrix shown in table 8D.1. Based on this scoring matrix, erosion, invasive species and pests, deforestation, and quarrying emerged as key threats to the basin's sustainability that required specific attention.

TABLE 8D.1 Criteria Used to Score Threats

THREAT	CRITERIA	SCORE
Severity	Light damage	1
	Moderate damage	2
	Very substantial damage	3
Footprint	Localized	1
	Widespread	2
Reversibility	Reversible	1
	Not reversible	2
Frequency	Sporadic	1
	Recurring	2

Source: Hesselbach et al. 2019.

Step 3: Multi-criteria analysis framework

The AMI is a large region of over 151,000 hectares, making it difficult and expensive to carry out conservation actions in the entire area. Therefore, multi-criteria analysis was used to identify specific priority sub-basins with greater potential for provisioning of water storage services, in terms of flood risk reduction and erosion control. The analysis was supported by quantitative models and a GIS platform through which thematic maps and maps of relationships between themes were generated, and results from other quantitative models were visualized and queried. The multi-criteria framework rests on three main components: inputs, criteria, and tools.

Inputs

Input data cover the physical geography characteristics of the area, the vegetation and soil type, and hydro-climatic information. This information was collected from historical datasets (maps of soils, water availability), remote sensing, and field work.

Criteria

The analysis comprises five criteria. These criteria were included to cover different aspects of the suitability of the sub-basin for flow regulation, flood risk reduction, and erosion control. The multi-criteria analysis focused on:

- **Soil vulnerability to vegetation loss.** This criterion quantifies the erosion risk due to vegetation loss. It is applied only to areas that are currently covered by vegetation, and it is therefore particularly important as it helps to track the potential contribution of vegetation conservation activities for reducing erosion risk.
- **Potential erosion.** This criterion quantifies the erosion risk in areas not covered by vegetation, for example, degraded lands or lands that have been altered by agricultural and livestock grazing activities. These areas cover approximately 10 percent of the AMI's surface area.
- **Surface runoff reduction potential.** This criterion measures the quantity of surface runoff generated by each sub-basin following a precipitation event. It is calculated as the difference in surface runoff per area (cubic meters per hectare) generated for a given precipitation event under different conservation and degradation scenarios (see step 4).
- **Flood control potential.** This criterion examines the flood control potential of different parts of the basin and for floods with different return periods. Flood control potential is estimated as the difference in peak flood discharge between the baseline and conservation/degradation scenarios in cubic meters per second.
- **Active river area (ARA).** The ARA includes both the channels and the riparian lands necessary to accommodate the physical and ecological processes associated with the river system (Smith et al. 2000). Given the importance of this indicator as a proxy for overall ecosystem health, it was selected to shed light on sub-basins that are particularly important for ecosystems and biodiversity.

Tools

The criteria above were used to guide to the multi-criteria analysis and were quantified through the application of four tools. Results from the four tools were combined to generate a map of priority sub-basins for the conservation of the green infrastructure of the sub-basins, and a GIS-based tool to inform the selection of investments. The four tools included:

- **Revised Universal Soil Loss Equation (RUSLE).** The RUSLE model is a commonly used method to estimate average annual soil losses, map erosion, and inform environmental restoration and soil conservation plans. For the AMI, the RUSLE equation quantifies the potential of the area to be eroded by diffuse erosion, that is, laminar erosion and in streams. The output is the average annual soil loss per unit area under the alternative scenarios. RUSLE was used to quantify criteria #1 and #2.

- **Surface runoff reduction calculator.** The "Guide for Replenishment," prepared by TNC and Quality Consulting Services S.A. (2014), is a tool for determining the surface runoff reduction potential (criterion #3) that a given type of vegetation cover can achieve. This calculator was used to estimate the surface runoff reduction potential.
- **ARA model.** This model estimates the river active area, that is, the flood area that allows for lateral river connectivity. The delimitation of the ARA is based on the methodology presented in Smith et al. (2008). The ARA is fundamental to determine the flood zones that allow lateral connectivity of rivers. It is calculated starting from the digital elevation models.
- **HEC-HMS hydrological model.** HEC-HMS is a semi-distributed hydrological model. This means that users need to define specific hydrological units (i.e., a sub-basin) with specific parameters describing their hydrological behavior (e.g., infiltration capacity, runoff coefficients). The rainfall-runoff model was used to test the performance of interventions—and combinations of interventions—on the ability of the priority areas to reduce peak flood discharge in the sub-basins located in the AMI. For the sub-basins outside the AMI, the hydrological model only simulated rainfall-runoff processes without modeling the impact of conservation or degradation processes (i.e., outside of the AMI, the model assumes that no degradation/conservation processes take place).

Step 4: Scenario analysis and identification of responses

To estimate the current and potential supply of hydrological environmental services, three scenarios were modeled: baseline, conservation, and degradation. The conservation and degradation scenarios consist of a simulation of changes in the hydrological condition of the vegetation cover and soils and the runoff coefficient with respect to the baseline, either by recovery and regeneration processes, or by deterioration of the current conditions. Recovery and regeneration processes contribute to improve the conditions of the vegetation cover and are expected to reduce erosion and regulate runoff.

The conservation scenario includes the following measures: (a) protection and restoration of vegetation cover; (b) erosion control; (c) forest management; (d) good agricultural and livestock practices; and (e) gray infrastructure, specifically, a new flood peak attenuation dam. For the first three, some practices are common and dual or multipurpose, such as the typical case of revegetation, and sometimes they are a combination of vegetation management with small structural measures, such as soil and water conservation works. The analysis also included a tool for species selection to be used in revegetation, designed in such a way that users could select them according to the objectives of the interventions, such as flood and erosion control, soil protection, or improvement of riparian zones.

To correctly model plant growth dynamics, the conservation and degradation scenarios also take into account the different stages of plant growth. The process simulates a gradual increase or loss of vegetation density, but without assuming a change in the type of potential vegetation cover. For the conservation scenario, the analysis differentiates the impacts that vegetation cover conservation activities would have on different types of cover, such as revegetation in pine forests and revegetation of scrublands, in such a way that changes in vegetation cover that are not feasible on the ground or contrary to the ecological dynamics of the study area are not proposed.

The tools were run to generate maps for each criterion under each alternative scenario. In this way, the sub-basins with greater or lesser need for action according to each one of the five criteria were identified. For each criterion, a sensitivity score from 1 to 5 was assigned to each sub-basin, defining quantitatively the lower or higher risk of degradation in the area or the greater or lesser influence of the area on the result of the analysis (in the case of the flood peak control criterion).

Results for each criterion were combined by summing each sensitivity score, resulting in a map of total sensitivity score where the highest score identifies sub-basins in which actions are most necessary (those in which the sensitivity values are highest). This results in a map of the AMI in which it is possible to clearly identify the priority of actions in the different sub-basin, depending on the total sensitivity score and also the underlying five criteria.

SOLUTION AND IMPLEMENTATION

The multi-criteria analysis demonstrated the ability of green infrastructure solutions to provide water storage services in terms of reduced runoff and erosion and improved water infiltration. More importantly, the analysis demonstrated that under a no action scenario, the basin's degradation processes would lead to higher runoff and erosion as compared to baseline levels. In other words, loss of green water storage leads to significant negative downstream impacts in terms of heightened flood risk and water quality deterioration. The latter impact can also increase the cost of water supply provision by increasing the costs of treatment.

While the modeling demonstrated that conservation activities can reduce runoff and help control erosion, it also showed that green infrastructure may not be enough to prevent flooding during extreme events. Given that the MMA has been built on both flood-prone areas of the Santa Catarina River, green infrastructure alone might not be sufficient to regulate flood peaks during events such as Hurricane Alex, which impacted the area in 2010. Hence, the watershed conservation plan also recommends the construction of a flood peak attenuation dam to reduce flood risks for events with return periods greater than 100 years.

The basin area where conservation interventions could be implemented is 124,608 hectares (82 percent of the AMI), which excludes rocky outcrops, river channels, urban areas, water bodies, and roads. For green water storage measures, areas with the following characteristics were excluded: slopes greater than 50 percent; a predominantly south-facing azimuth, since the high exposure to solar radiation increases potential evapotranspiration, reducing the speed of plant growth and survival rate; and stone slab outcrops, where vegetation growth is naturally limited.

The conservation plan gives a strong direction to the water fund's work, concentrating it on a strategically targeted area covering over 124,000 hectares. While this covers only around 5 percent of the San Juan River Basin, the conservation plan shows that they are highly sensitive and located in parts of the watershed that produce approximately 60 percent of Monterrey's water supply (Abell et al. 2017). This highlights the importance of carefully targeting rehabilitation of green water storage through quantitative analysis to maximize the impact of interventions.

Based on the watershed conservation plan, FAMM is implementing the following actions over an initial area of about 5,500 hectares. The interventions include: 1,300 hectares of active reforestation; 3,000 hectares placed under conservation through payment for ecosystem services (PES); 1,200 hectares acquired for conservation; 77 hectares benefitting from passive reforestation; and 58 hectares from soil conservation. At the time of writing, about $10 million (IDB 2018) has been contributed into the fund and invested in reforestation, targeted land protection, soil conservation, and PES.[1] The PES spans 124 participants, including both private landowners and farmers on communal land property.

Building upon the experience of the creation of the water fund and the identification of green storage options in the upper catchment, the FAMM began a multi-stakeholder and long-term water planning process in 2016 for Monterrey and the State of Nuevo León. This resulted in the development of the Nuevo León 2050 Water Plan, a long-range water strategy informed by decision-making under deep uncertainty methods and stakeholder consultations (Molina-Perez et al. 2019). The 2021–22 drought demonstrates that Monterrey remains highly vulnerable to hydro-climatic extremes. As the city grapples with more severe drought and the prospect of Day Zero events, the relevance and urgency of implementing a broad portfolio of storage solutions grounded in evidence and systematic analysis increases even further.

LESSONS LEARNED

» **Don't wait for a crisis but don't waste one.** The impetus for creating the water fund and then promoting a watershed conservation plan came from the impact in 2010 of a huge flood (Hurricane Alex), followed by an extensive drought (2011–13). Climate extremes provide openings to raise the profile of water management issues on the political agenda and oftentimes to build the necessary momentum around beneficial investments in water storage.

- **Intermediaries and special purpose instruments, such as water funds, are strong enablers for investments in nature-based solutions for water storage.** This is because they facilitate partnership for innovation, ensure coordination among stakeholders, and are pooling resources and mitigating financial risks. This means that without the FAMM, investments in nature-based solutions were not going to take place.
- **Appraisal of green storage options and quantification of their benefits require utilization of multiple performance criteria and tools.** The case study's multi-criteria approach demonstrates the importance of (a) considering multiple criteria when evaluating the benefits of green storage solutions and (b) employing different tools to quantify these benefits. A plurality of tools is also required to ensure that the interactions of green storage solutions with other components of the sub-basin (e.g., topography, soil cover type) are taken into account when quantifying benefits such as flood peak attenuation and erosion risk reduction.
- **Conservation and protection of ecosystems is a key measure to rehabilitate water storage.** The case study shows that ecosystems provide key water storage services, notably to reduce surface runoff and erosion risk. Investments to rehabilitate ecosystems, protecting them from degradation and actively improving their conditions, need to be an integral part of a diversified water storage portfolio.

ENDNOTES

1 Hilda Hesselbach, interview by World Bank, 2022.

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ANNEX 8E. INDONESIA: GETTING MORE FROM EXISTING BUILT STORAGE: PRIORITIZING REHABILITATION INVESTMENTS

CASE STUDY BRIEF

Summary

Indonesia shifted its approach to dams from a project-by-project approach to a “portfolio approach” that recognizes the strategic function of existing dams in addressing water stress and water insecurity in the country. Because of Indonesia's unique geography as the world’s largest archipelago, with extreme rainfall variability yet limited natural storage, its built water storage infrastructure plays a significant role in improving the local availability and reliability of water to its population and industries as well as in the country’s resilience against droughts and floods. However, despite decades of investment in new dams, the performance of many dams is declining due to aging, sedimentation, and lack of funding for operation and maintenance. Indonesia evolved its institutional framework from establishing basic dam safety and management provisions to the introduction of integrated water resources management (IWRM) as a guiding framework. The shift to a portfolio approach also includes the adoption of portfolio risk assessment and risk management for dams to prioritize investments as well as measures to improve the sustainability of financing for operation and maintenance.

Type(s) of water storage used

- Large reservoirs
- Small reservoirs/retention structures

Water service(s) of storage provided

- Increased water availability
- Flood mitigation
- Flow regulation

Water requirement(s) of storage met

- Water provision for domestic needs and industrial processes
- Water provision to meet crop/livestock requirements in seasons/locations without precipitation
- Water provision to meet crop/livestock requirements throughout the growing season
- Water controlled for electricity generation
- Prediction and attenuation of excess water for risk reduction

BACKGROUND

Water storage is key to Indonesia's growth and development. Indonesia is the largest archipelago in the world and the fourth most populous nation with over 276 million inhabitants. Gross national income per capita has risen steadily from $4,430 in 2000 to $11,750 in 2020, halving the poverty rate from 19.1 percent in 2000 to 9.8 in 2020 (World Bank 2022). Notwithstanding these massive economic gains over the past 20 years, Indonesia still has a large share of its population living below the national poverty line and significant wealth disparities across different parts of the country, especially in rural areas. Water security and water storage are key to resolving some of the constraints to Indonesia's development and achieving shared prosperity.

Even though Indonesia has abundant water resources in aggregate terms, these resources are unevenly distributed across an archipelago of more than 17,000 islands that extends across 5,000 kilometers in length. In Kalimantan and Papua, there are larger river basins, but the more densely populated areas, where water demands are higher, are served by smaller river basins with limited retention capacity (World Bank 2021). For three quarters of the basins, demand for water is already close to or outstripping supply, leading to conditions of water stress (World Bank 2017a).

In addition to the country's unique geography and the pressures of population growth and urbanization, there is significant seasonal variability with pronounced wet and dry periods. This high degree of seasonality leads to seasonal water shortages, which is especially acute in Java, home to Indonesia's capital city, Jakarta. Java has less than 5 percent of the nation's water resources for nearly 60 percent of its population. The densely populated and rapidly urbanizing islands of Java and Bali are also prone to drought and flood hazards, which are linked to the El Niño-Southern Oscillation and increasingly being worsened by climate change. Water storage is essential for increasing water availability in higher density areas, managing seasonal variability, and building resilience to floods and droughts (World Bank 2017a).

As most of the rivers surrounding its larger population centers have steep gradients and their retention capacity is limited, Indonesia has sought to increase its available water storage through the construction of small and large dams (World Bank 2017a). Most large cities, such as Greater Jakarta, Surabaya, Makassar, and Semarang, depend on reservoirs and barrages for a major portion of their water supply. One large reservoir accounts for about 80 percent of Greater Jakarta's tap water (World Bank 2009a and 2017b). Today, the country has an extensive network of more than 2,200 dams, 213 of which are classified as large. These dams provide the full range of enabling storage services, including improving the availability of water for irrigation, and regulating flows for hydropower generation, and some provide storage of peak flood waters. In 2014, there were 228 large dams registered with a volume of 13.8 bm^3, of which 186 were owned by the Ministry of Public Works and Housing (MPWH). Another 42 dams with storage volume of 6.65 m^3 were privately owned. Since then, the government has embarked on a program to construct 61 new dams, of which 29 are completed. The dams serve a number of purposes, including irrigation, flood control, bulk water supply, and hydropower generation, and many of the dams are multipurpose interventions (MPWH 2022).

PROBLEM DEFINITION

Closing the Water Storage Gap

Despite decades of investment, Indonesia ranks low in per capita storage capacity, and this is severely constraining its economic development and achievement of its food security goals. With an estimated reservoir storage capacity of 71 m^3/capita, Indonesia lags far behind its neighbors such as Malaysia (710 m^3/capita), Thailand (1,006 m^3/capita), Vietnam (310 m^3/capita), Japan (228 m^3/capita), and India (190 m^3/capita) (World Bank 2021).

Indonesia's natural storage capacity is also being threatened by progressive degradation of the country's catchments as well as sedimentation induced by soil erosion linked to volcanic activity. Land-use change is also a challenge with approximately 20,000 hectares/year of prime irrigated paddy fields being converted to other uses to accommodate the needs of its urbanizing population (World Bank 2017a).

The government seeks to grow the country's per capita water storage capacity to 100 m³/capita to increase water, food, and energy security. Toward this goal, it is in the process of developing 61 new dams by 2025 while safeguarding its existing reservoir storage capacity through improved operation, maintenance, and safety (MPWH 2022; World Bank 2017a) (map 8E.1).

Better Operation and Maintenance Is Needed

Indonesia's fleet of existing dams is aging, and many dams have declining performance and safety deficiencies that need to be addressed. Of the 213 large reservoirs in the country, 31 were built before 1980, and of those 31, 16 were built before 1950. The ability of those reservoirs to deliver storage services is being hindered by old or damaged electromechanical systems that no longer function, and premature sedimentation that has reduced storage volume in approximately 30 reservoirs and increased safety risks for those dams (World Bank 2009a).

In addition to the physical condition of the dams and reservoirs, their performance is also affected by operational and management practices. At the time that Indonesia

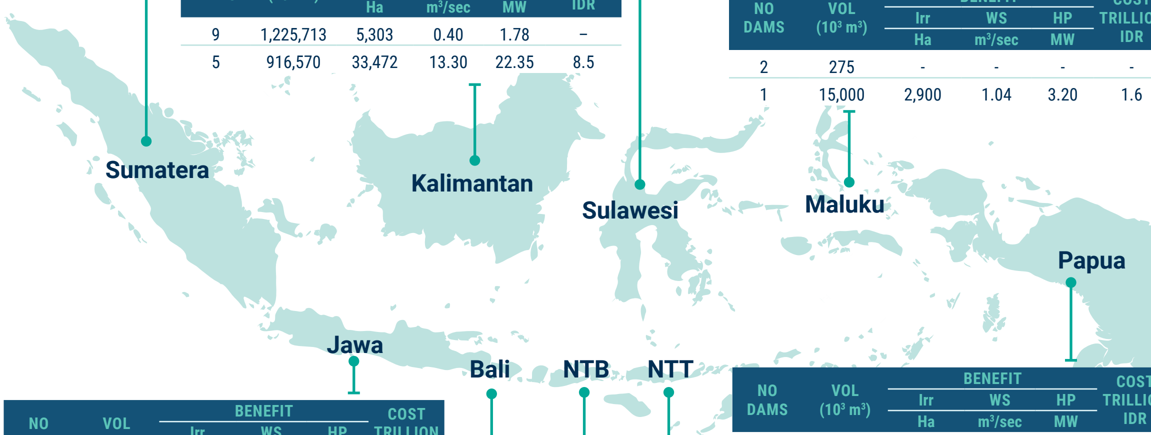
MAP 8E.1 Distribution of Existing and Planned Dams in Indonesia

NO DAMS	VOL (10^3 m^3)	BENEFIT Irr Ha	WS m^3/sec	HP MW	COST TRILLION IDR
20	2,850,000	118,467	988	7.97	–
11	985,000	88,002	9.59	108.34	11

NO DAMS	VOL (10^3 m^3)	BENEFIT Irr Ha	WS m^3/sec	HP MW	COST TRILLION IDR
9	506,055	36,684	515	2.5	–
9	1,380,620	75,217	9.20	35,68	10

NO DAMS	VOL (10^3 m^3)	BENEFIT Irr Ha	WS m^3/sec	HP MW	COST TRILLION IDR
9	1,225,713	5,303	0.40	1.78	–
5	916,570	33,472	13.30	22.35	8.5

NO DAMS	VOL (10^3 m^3)	BENEFIT Irr Ha	WS m^3/sec	HP MW	COST TRILLION IDR
2	275	-	-	-	-
1	15,000	2,900	1.04	3.20	1.6



NO DAMS	VOL (10^3 m^3)	BENEFIT Irr Ha	WS m^3/sec	HP MW	COST TRILLION IDR
0	–	–	–	–	–
1	200,000	–	–	50.00	4.7

NO DAMS	VOL (10^3 m^3)	BENEFIT Irr Ha	WS m^3/sec	HP MW	COST TRILLION IDR
91	8,600,000	726,048	4,609	51.94	-
24	2,674,370	222,841	24.93	154.96	26

NO DAMS	VOL (10^3 m^3)	BENEFIT Irr Ha	WS m^3/sec	HP MW	COST TRILLION IDR
15	33,525	4,926	–	–	–
7	216,590	14,696	1.44	3.90	5.6

NO DAMS	VOL (10^3 m^3)	BENEFIT Irr Ha	WS m^3/sec	HP MW	COST TRILLION IDR
5	27,158	5,230	1.5	0.53	-
3	29,600	7,586	3.74	3.86	2

NO DAMS	VOL (10^3 m^3)	BENEFIT Irr Ha	WS m^3/sec	HP MW	COST TRILLION IDR
62	270,148	51,229	0.48	0.47	-
4	99,920	12,134	0.75	10.30	2

Source: World Bank 2018.
Note: HP = hydropower; Irr = irrigation; NTB = Nusa Tenggara Barat (West Nusa Tenggara); NTT = Nusa Tenggara Timur (East Nusa Tenggara); WS = water supply.

was launching its program to restore dam performance and safety, several dams lacked basic operations manuals, sufficient instrumentation for hydrological and dam safety monitoring, and dam safety plans (World Bank 2009a).

Funding for operation and maintenance of dams is also a challenge. Dam operation and maintenance is funded from national budgets through government transfers to provincial-level and ultimately district-level institutions, but funding is constrained by resource availability and complexity of the fiscal arrangements. Irrigation spending is largely focused on capital investments for new construction and rehabilitation, with insufficient allocations for operation and maintenance. In 2012, the MPWH estimated that the funds needed for operation and maintenance were approximately Rp 250,000/hectare on average for the national irrigation system, but the actual budget for that year was only Rp 180,000/hectare, increasing to Rp 200,000/hectare in 2013 (World Bank 2017a). It is currently in the range of Rp 500,000 to 800,000/ha depending on the locations and needs.

The government has sought not only to remedy the immediate challenge of declining reservoir performance but more broadly to ensure the safety and performance of all existing and newly constructed dams in Indonesia. Beyond the rehabilitation works for the dams currently at risk, the challenge includes providing an enabling institutional framework for managing dams, securing a dedicated revenue stream to support long-term operation and maintenance, and strengthening Indonesia's technical capacity with more skilled professionals to improve dam management and safety. This requires a shift away from the facility-by-facility approach to managing dams and reservoirs to more of a systems approach, implementation of a long-term program with phased investments, and continued progress on the institutional reforms needed to support such a shift.

INSTITUTIONS AND INSTITUTIONAL FRAMEWORK

The main institutions involved in this case study are (figure 8E.1):

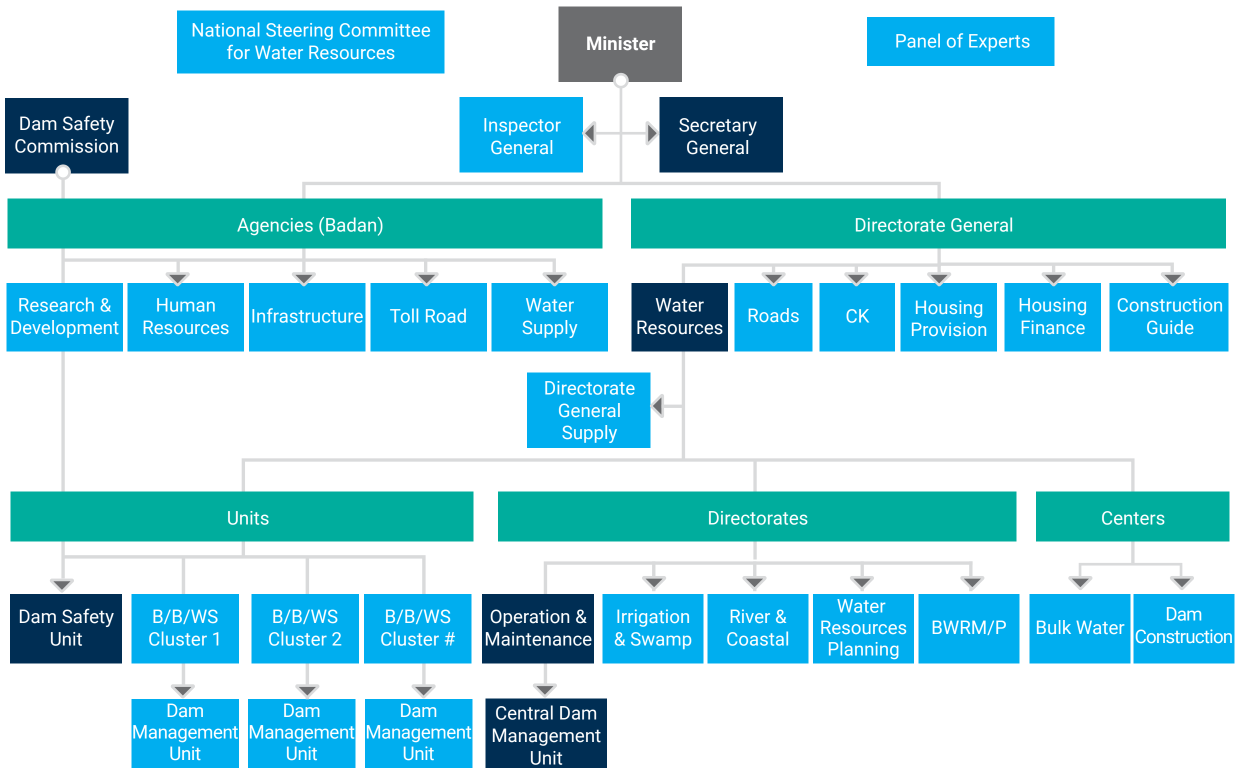
- **The MPWH,** which owns the vast majority of the large dams in Indonesia and is the umbrella ministry under which the institutions responsible for dam safety are established. Under the MPWH are:
    - **The Dam Safety Commission (DSC),** which is chaired by the Minister of Public Works and Housing. The DSC is responsible for the certification of dams during construction and special events during operation. All development stages are subject to licenses issued by the minister upon recommendation by the DSC.
    - **The national Dam Safety Unit (DSU),** established in the Directorate General of Water Resources (DGWR) within the MPWH, serves as the implementation unit for the DSC and carries out inspections, evaluation of requests for licenses, and provision of guidelines related to dam operation, maintenance, and safety.
    - **The Central Dam Monitoring Unit (CDMU),** which was established in the Directorate of Operations and Maintenance, executes oversight of the portfolio of existing dams under the responsibility of the MPWH.
    - **Dam Monitoring Units (DMUs)** within river basin organizations carry out day-to-day management of individual dams and carry out systematic monitoring and reporting on the situation of each dam to the CDMU (World Bank 2017a).

THE EVOLUTIONARY PROCESS: TOWARD A SYSTEMS APPROACH

1990s: The First Dam Safety Project

In 1994, the Government of Indonesia began its first Dam Safety Project (DSP), aimed at reducing the risk of dam failure in Indonesia. It was the World Bank's first project dedicated to dam safety in Indonesia and its second ever after the India DSP, approved three years prior. The Indonesia DSP supported the government in introducing a basic institutional framework for dam management and safety, including the constitution of the DSC, DSU, and CDMU under the DGWR (World Bank 2009b). A 2004 Ministerial Decree for Dam Safety was passed, followed by 1997 Ministerial Regulation No. 72/PRT/1997 "Regarding Dam Safety," which laid out the first national guidelines for dam safety (World Bank 2009a). Under the project, the provincial DMUs were also established in eight provinces.

FIGURE 8E.1 Organogram of the Dam Safety Institutions within the MPWH, Indonesia



Source: Adapted from World Bank 2017a.
Note: Dam safety institutions within the Ministry of Public Works and Housing (MPWH) are shown in dark blue.

Late 1990s to 2000s: Institutional Reform and the Introduction of IWRM

In 1999, the Government of Indonesia began a process of reforming the legal, regulatory, and administrative framework for its water resources sector, including on dam safety. The 2004 Law on Water Resources (UU 7/2004) paved the way for the introduction of decentralized, basin-based IWRM. Under this law, all river basins were to have long-term strategic plans and master plans focused on water resources conservation, high-quality service delivery, and increasing institutional capacity of water management institutions. The law also aimed to improve governance of hydraulic infrastructure and enable a more programmatic approach to dam and reservoir management (World Bank 2017a).

A series of regulations were subsequently introduced by MPWH, including:

- Ministerial Regulation No. 11a/PRT/M/2006 by the MPWH, which defines 133 river territories.
- Government Regulation on Dams (37/2010), which lays out an improved framework for dam safety and management for the large dams managed by MPWH (figure 8E.1).
- Government Regulation on Dams (37/2013), which provides improved regulations, guidelines, and administrative capacity (World Bank 2017a).

However, Law 7/2004 on Water Resources was overturned by Indonesia's Constitutional Court,[1] thus reinstating the previous 1974 Water Law as the controlling legislation (Library of Congress 2015). From 2015 to 2019, the construction and management of dams was temporarily governed through Ministerial Regulation No. 27/2015 and Ministerial Decree No. 03/KPTS/M/2016 on DSC (World Bank 2017a, 2018).

2010s: Shifting to a Portfolio Approach for Managing Dams and Reservoirs

With the first DSP, the Government of Indonesia began to invest in better management and development of dams, but still these dams were being treated as individual pieces of infrastructure without a broader strategic perspective on how they fit together. For decades, the government prioritized rapid development of new infrastructures without due consideration to the resources needed for operation and maintenance. While this focus on new construction spurred economic growth and increased productivity in agriculture, it contributed to deferred maintenance and sub-optimal use of existing dams and reservoirs (World Bank 2009a).

A new program spearheaded by the MPWH introduced a portfolio approach for management of dams in Indonesia, whereby dams and reservoirs are treated as infrastructure of strategic importance for securing bulk water and providing other critical water storage services. A series of projects financed by international development partners such as the World Bank and the Asian Infrastructure Investment Bank supported the introduction of portfolio risk assessment and portfolio management to inform the prioritization of investments to improve the safety and functionality of large MPWH-owned reservoirs (World Bank 2017a).

SOLUTION ADOPTED AND IMPLEMENTATION

Applying Portfolio Risk Management Approaches to Existing Dams and Reservoirs

The MPWH developed a dam risk assessment to prioritize the rehabilitation of the most at-risk dams. The method used has been modified from the one introduced in ICOLD Bulletin 72 "Selecting Seismic Parameters for Large Dams" (ICOLD 1989) (figure 8E.2). The risk assessment criteria used can be divided into two groups:

1. Characteristics of the dam itself, including reservoir capacity, dam height, and construction, as well as maintenance data, monitoring data from instruments, and previous remedial works done to address safety deficiencies; and
2. Factors related to the dam, including potential downstream consequences of dam failure, evacuation requirements, and business risks.

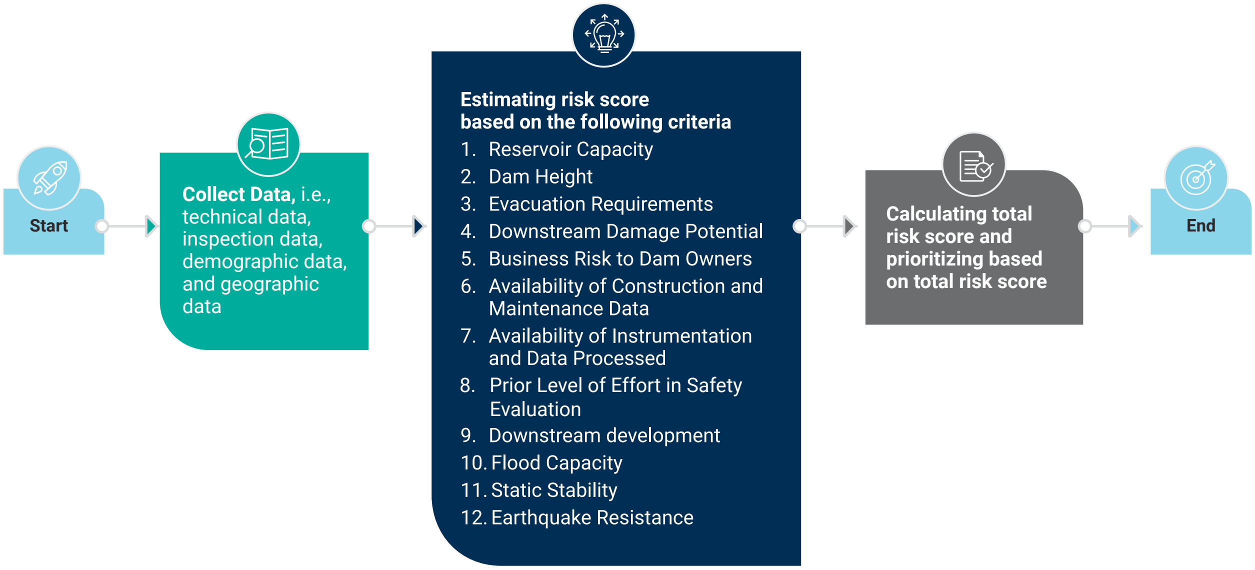
The risk values are determined and arranged into risk classes: extreme, high, moderate, and low (Soentoro, Purnomo, and Susantin 2013).

Under the Dam Operational Improvement and Safety Project (DOISP) Program, the MPWH initially identified a short list of 63 dams for safety and functionality improvement works. Among those, 30 were being affected by accelerated sedimentation. These 63 dams had a total downstream population at risk of 9.5 million people and could cause flood damage and loss of irrigated area of 310,000 hectares (World Bank 2009a). Using the modified ICOLD risk assessment method, a prioritized list of 34 dams was developed in order to give priority treatment to more urgent rehabilitation works given the funding available (DGWR 2008). These dams were successfully rehabilitated under the program between 2009 and 2017, and an additional 120 dams were then included under subsequent phases of the program with the aim of reducing the safety risks in the portfolio by more than 20 percent (World Bank 2017a). Under the World Bank-financed DOISP phase 2 project, a new guideline on risk assessment for dams using the modified ICOLD method has been prepared but has not yet been institutionalized.

Sustainable Financing for Operation and Maintenance of Existing Dams

To improve cost recovery and to ensure the financial sustainability of river basin management systems, the Government of Indonesia established two self-financing state enterprises, or river basin corporations (PJT I Banta's and PJT II Jatiluhur), under the Ministry of State Enterprises. These state-owned companies are responsible for the operation and maintenance of hydraulic infrastructure with funding derived from raw water sales, hydroelectricity, and various fees (World Bank 2017a). Under the DOISP program, the MPWH has adopted needs-based budgeting and piloting of performance-based contracts (World Bank 2017a). To date, allocations for operation and maintenance of dams have increased, coming closer to the needs-based budget for operation and maintenance.

FIGURE 8E.2 Modified ICOLD Risk Analysis Method



Source: Adapted from Soentoro, Purnomo, and Susantin 2013.

Preventative and Mitigating Measures for Reservoir Sedimentation

Comprehensive sediment management, employing a community incentive-based approach for watershed management, is also a key part of the program to prolong the life of Indonesia's reservoirs, increase their performance with regard to water availability, and reduce the incidence of flooding and landslides. Corrective measures include dredging, reservoir flushing, sediment traps, check dams, and stabilization works while preventative measures such as catchment management is addressing sedimentation at the source (World Bank 2017a).

LESSONS LEARNED

A focus on institutional development needs to be sustained over the long term. Starting with the DSP, which launched in 1999, the Government of Indonesia initiated the development of a basic institutional and regulatory framework for the management and safety of dams, which was followed by subsequent reforms over two decades. This included changes at the legislative level and the promulgation of more detailed regulations. Legal and institutional reform is a continuous process, which may not be linear as demonstrated by the repeal of Water Law 7/2004 and the eventual passage of the new 2019 Water Resources Law.

Risk analysis methodologies and phased approaches are useful for prioritizing investments for large infrastructure portfolios. In the case of Indonesia, with more than 2,200 dams, including more than 200 large dams, it is not always possible to address rehabilitation needs in the scope of a single project. The use of a programmatic approach to financing the needed rehabilitation work coupled with the use of the modified-ICOLD risk analysis method was important for prioritizing investments to where they are most critical given limited financial resources.

Recognizing the need to safeguard and prolong the life of existing water storage assets is an essential part of addressing a water storage gap. The Government of Indonesia has a target for new storage investments but also has prioritized the rehabilitation and restoration of existing reservoir capacity lost to sedimentation, aging structures, and deferred maintenance. Dam safety investments were also essential in safeguarding against damage and loss of life downstream that could have occurred due to dam failure, which would also have exacerbated the storage challenge by removing reservoir capacity from the system and likely making it more politically and administratively difficult to invest in new dams.

ENDNOTES

[1] Law 7/2004 was repealed because it had permitted private sector companies to sell packaged tap water, which was ruled unconstitutional because, under the Constitution, the right to water is a basic right and its control is a mandate of government.

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ANNEX 8F. NAMIBIA: CONJUNCTIVE SURFACE AND GROUNDWATER MANAGEMENT FOR DROUGHT RESILIENCE IN WINDHOEK

CASE STUDY BRIEF

Summary

Motivated by chronic water shortages and frequent droughts, the City of Windhoek, together with national water institutions, has responded with a wide range of measures to improve the city's water security. This included raising new built storage infrastructure, investing in direct potable reuse, implementing water demand management and conservation measures, and exploiting the strategic potential of the Windhoek Aquifer as a "water bank" that is protected from the high rates of evaporation experienced by its surface storage and conveyance infrastructure.

Though most of the elements of the current water storage and bulk water supply system pre-date the adoption of an integrated water resources management (IWRM)–guided planning framework, the city's many innovations have resulted in a physically interconnected system of surface and groundwater storage that utilizes diversified water sources to improve drought resilience, reduce evaporative losses, and provide flexibility.

Type(s) of water storage used

- Aquifers
- Large reservoirs

Water service(s) of storage provided

- Increased water availability

Water requirement(s) of storage met

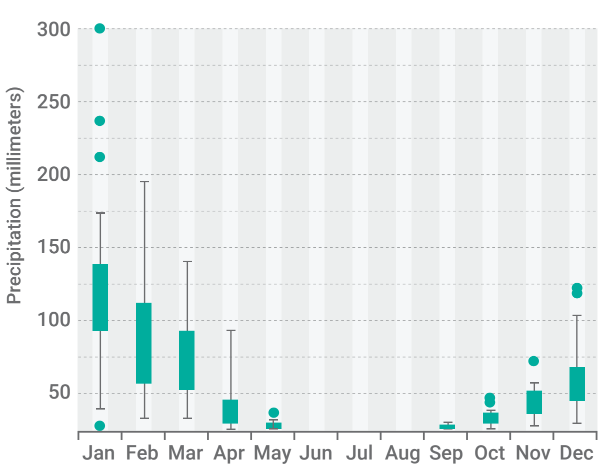
- Water provision for domestic needs and industrial processes

BACKGROUND

In Sub-Saharan Africa, Namibia is one of the driest countries. Situated between the Namib and Kalahari deserts, Namibia has an arid climate with limited, sporadic rainfall and low soil moisture. Its mean annual precipitation between 1901 and 2016 was just 277.6 millimeters (World Bank 2021b), which ranks in the bottom sixth of countries worldwide (World Bank 2017). Rainfall is extremely variable throughout the year with virtually no rainfall between June and August (figure 8F.1). High solar radiation and temperatures combined with low humidity produce very high evaporation rates that vary between 3,800 millimeters per year in the southern parts of the country to 2,600 millimeters per year in the northern parts (World Bank 2021a). Like other countries in Southern Africa, drought is a frequent occurrence in Namibia and poses a significant risk for the agriculture sector, which is the mainstay of the country's rural population (World Bank 2021c).

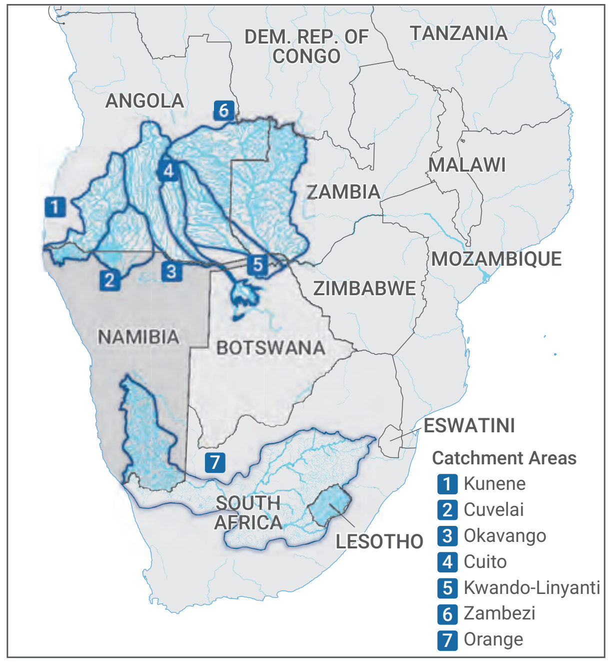
Both surface and groundwater resources in Namibia are very limited. About 97 percent of Namibia's rainfall is lost to evaporation and evapotranspiration, with precipitation often evaporating before it reaches the ground. This leaves only 3 percent of precipitation available to form surface runoff or recharge aquifers. All of Namibia's perennial rivers are transboundary rivers shared with other countries (map 8F.1), including the Orange River in the south and the Okavango, Kunene, Kavango and Zambezi Rivers in the north (World Bank 2021a).

FIGURE 8F.1 Distribution of Precipitation in Namibia



Source: World Bank 2021b.

MAP 8F.1 Perennial Rivers of Namibia



Source: Adapted from Mendelsohn et al. 2002.

Namibia and its capital Windhoek, the country's largest city, rely heavily on surface and groundwater storage to meet its bulk water supply needs. Perennial border rivers account for 33 percent of Namibia's water supply while 22 percent comes from impoundments on ephemeral rivers that carry water in the interior of the country. Groundwater accounts for 45 percent, including alluvial groundwater stored beneath ephemeral rivers (World Bank 2021b). The City of Windhoek relies on its "three-dam system," managed by the Namibia Water Corporation Ltd. (NamWater), as well as the Windhoek Aquifer to the south of the city and other aquifers in the northern areas of the city for most of its bulk water supply. The city also recycles its wastewater, which is put back into the city's water supply as well as stored underground during periods of excess (City of Windhoek 2019; Taylor 2019).

Windhoek is considered a world leader in managing scarce water resources. Windhoek is a small but fast-growing city located in the Central Area of Namibia. At the time of the most recent census in 2011, Windhoek had a population of 325,858, with a high annual growth rate of 3.3 percent (NSA 2011). Windhoek is home to 36 percent of the total urban population in the country, and its population is expected to more than double by 2050 (Scott et al. 2018; Murray et al. 2018). The city is well-known for its innovation in water management and is recognized as the first city that implemented wastewater recycling for direct potable reuse (Taylor 2019; World Bank 2021c).

PROBLEM DEFINITION

Population and economic growth are putting increasing pressure on Windhoek's already limited water resources. Around the time of its original settlement in the late 1800s, Windhoek was considered to have sufficient water because of its natural springs, but as the city grew and developed, existing groundwater sources became inadequate (Mapani 2005). New boreholes were drilled to increase pumping from the Windhoek Aquifer, and by 1942 the aquifer was depleted. Still, large-scale abstraction continued, and Windhoek was considered to have exceeded its natural geographic water resources availability (Taylor 2019; Mapani 2005; MAWLR 2020). By 2010, even with the development of alternative sources, it was becoming apparent that the city's supply was approaching the capacity of the system to meet demand. In 2019–20, water demand in Windhoek was estimated at a managed 24 million m^3 (projected at 28 million m^3 without demand management and conservation). By 2034, demand is expected to reach 36.47 million m^3, including demand management and conservation measures (MAWLR 2020; Zheng et al. 2021).

In addition to its natural water scarcity, Namibia generally and the City of Windhoek specifically have been experiencing more frequent and more severe droughts due to climate change. In 2015–16, much of Southern Africa experienced a rapid but devastating "flash drought," when the onset of drought is unusually rapid, a type of event that has occurred much more frequently since the 1960s. This was followed by a severe drought in 2015–17, which caused inflows into the Von Bach Dam—one of the three main dams in the Central Area around Windhoek—to fall to zero for the first time since its construction. The 2018–19 drought that followed was considered the worst drought to hit the country in 90 years, with the lowest rainfall recorded in Windhoek since 1891 (van Rensburg and Tortajada 2021). This drought resulted in widespread food shortages, some 60,000 livestock deaths across Namibia, and a decline in cereals production by up to 80 percent. With climate change, Namibia is expected to see an increase of between 1.5°C and 2.97°C in mean temperature by 2040–59 and a decrease in annual precipitation by 40.9 millimeters (RCP 8.5, Ensemble), which will increase the impacts of drought (World Bank 2021b). The share of gross domestic product potentially affected by drought is currently about 41 percent on average—this is equivalent to $4 billion each year (UNDRR and CIMA 2018). Under future climate and socioeconomic conditions, however, the share of GDP produced in areas hit by drought could reach 90 percent, equivalent to almost $10 billion (World Bank 2021b).

INSTITUTIONS AND INSTITUTIONAL FRAMEWORK

Main Institutions and Responsibilities

The main institutions governing water storage and bulk water supply in Windhoek are NamWater, the City of Windhoek, and Namibia's Ministry of Agriculture, Water and Land Reform (MAWLR), formerly the Ministry of Agriculture, Water and Forestry.

NamWater is the national agency that owns and operates bulk water infrastructure across the country and is tasked with providing bulk water to different types of customers, including municipalities and local authorities, government institutions, industrial customers, and mines. It also supplies water to a select number of retail customers that live in proximity to its pipelines. For the Central Area, where Windhoek is located, NamWater operates seven surface water dams and 297 boreholes. NamWater was established in 1997 and is fully owned by the Government of Namibia (NamWater 2020).

MAWLR has overall responsibility for water resources management in Namibia. It has eight directorates, including:

- **The Directorate of Water Resources Management,** tasked with promoting sustainable and equitable water resources management and use, allocating water and regulating abstraction, and strategic planning; and
- **The Directorate of Water Supply and Sanitation Coordination,** tasked with providing access to potable water supply and sanitation in rural areas, coordi-

nating urban water supply and sanitation services (MAWF 2017).

The Department of Infrastructure, Water and Technical Services (City of Windhoek) supplies, distributes, and ensures the quality of water in the Windhoek urban area. It supplies water to city customers from the Windhoek Aquifer through several production boreholes that it owns (with permits from MAWLR), reclaimed water, as well as with bulk water purchased from NamWater (Scott et al. 2018). The city is the owner and operator of the Windhoek Managed Aquifer Recharge Scheme (WMARS) and has developed plans for water demand management that helps the city manage water supply and use under varying supply conditions, including drought. Its actions are informed by supply situation indicators provided by NamWater (City of Windhoek 2019). The city also has an operations and maintenance contract with Windhoek Goreangab Operating Company (WINGOC), a private consortium of Veolia and VA Tech Wabag, which is responsible for operating the New Goreangab Water Reclamation Plant that provides reclaimed water treated to potable standards.

Enabling Framework

Over the last decade, Namibia has been enacting homegrown water legislation and regulations. Until 1990, Namibia was a protectorate under the stewardship of South Africa, and because of this, much of the legislation in force during the development of major elements of its bulk water supply and storage infrastructure has origins in South African law. This includes the Water Act of 1956.

In 2000, the Namibian government issued the National Water Policy White Paper, which provided a guiding framework for the adoption of IWRM, including alignment of Namibia's policy framework with the Agenda 21 action plan from the 1992 Earth Summit and the Dublin Principles from the 1992 International Conference on Water and the Environment (MAWLR 2020). National legislation and regulations pertaining to water resources management were also enacted over the last decade, including the Water Resources Management Act (Act 11/2013), which is intended to replace the Water Act (Act 54/1956), but at the time of this case study, the new law had not yet entered into force (MAWLR 2020).

THE EVOLUTIONARY PROCESS: A SYSTEMS APPROACH

Groundwater Overexploitation and Surface Water Impoundments

Before 1933, all of Windhoek's water came from the Windhoek Aquifer. But as the city's population growth drove water demand to exceed the sustainable yield of the aquifer, efforts were made to diversify its water supply, specifically the construction of Avis Dam on the Avis River, which runs through Windhoek, with a reservoir capacity of 2.4 million m^3. However, the catchment area of Avis Dam is very small, and the dam was often unable to supply any water at all; today, it is part of a nature reserve and used exclusively for recreation (du Pisani 2006). A second dam was completed in 1958 to the west of the city—the Goreangab Dam with a reservoir capacity of 3.6 million m^3 (du Pisani 2006; Mapani 2005).

Despite the investments in surface water impoundment, however, exponential growth in water demand led groundwater abstraction at Windhoek to an unsustainable 4.28 million m^3/year by 1969. For comparison, the natural recharge rate of the aquifer is estimated at around 1.73 million m^3 per year on average. This water crisis inspired efforts to augment the city's supply with water from other parts of the country (Mapani 2005; Murray et al. 2018).

1968: Introducing Direct Potable Reuse

Spurred by the growing crisis, the City of Windhoek introduced its first direct potable reuse facility in 1968, informed by a research project conducted jointly by the City of Windhoek and the National Institute of Water Research in South Africa (Haarhoff and Van der Merwe 1996). The conventional water treatment plant at Goreangab Dam was converted into a reclamation plant to treat both the water impounded in the Goreangab Reservoir and the effluent coming from the Gammams wastewater treatment plant, the main wastewater treatment facility for the city (du Pisani 2006). Much of the water behind Goreangab Dam, however, was unfit for reclamation as the whole city, including industries and informal settlements, was located in the catchment area for the dam. Thus, the city undertook to separate domestic and potentially harmful industrial wastewater, diverting industrial wastewater to a different facility. It also undertook zoning reform to locate certain industries in the northern part of the city so that its wastewater could be separated (du Pisani 2006; Haarhoff and Van der Merwe 1996). This industrial zoning would also become part of the city's strategy to protect the Windhoek Aquifer recharge areas later on.

1970s–1980s: The Three-Dam System

Meanwhile, efforts were also being made to increase the amount of surface water available to the city. In 1970, the Von Bach Dam was commissioned on the Swakop River—the first of the three interconnected dams that are often referred to as Windhoek's "three-dam system." The other two dams are the Swakoppoort Dam, also on the Swakop River, commissioned in 1977, and the Omatako Dam on the Omatako River, commissioned in 1982. All three dams are built on ephemeral rivers to capture and store water for dry periods and are designed to store up to three times the mean annual runoff (Sirunda and Mazvimavi 2014).

In addition to annual inflows, water in the three-dam system is augmented by transfers from the karst aquifer near Grootfontein, north of the Central Area. Despite high evaporative losses, this three-dam system and water transfer scheme significantly increases the amount of water available to Windhoek, and under normal meteorological conditions, supplies between 70 and 75 percent of the city's water (Taylor 2019; van Rensburg and Tortajada 2021) (table 8F.1).

The three dams are operated as a system by NamWater; raw water is transferred from the Swakoppoort and Omatako reservoirs via pipeline to the Von Bach Reservoir. The purpose of the transfer scheme is twofold: to bring the water closer to the treatment plant at Von Bach, which is the closest of the three dams to the city, and more importantly, to limit the amount of water lost to evaporation (Sirunda and Mazvimavi 2014; van Rensburg and Tortajada 2021). The reservoir at Von Bach is deeper and narrower, giving it a smaller surface area than that of Swakoppoort and Omatako. To gauge the significance of evaporative losses, consider that the comparative water remaining in Omatako, Swakoppoort, and Von Bach dams after one year's evaporation, assuming they are 100 percent full at the start of the year and have no inflow during the year, would be about 39 percent, 75 percent, and 78 percent, respectively. This operational regime improves the 95 percent safe yield to 20 million m^3 per year compared to if the dams were operated on an individual basis (MAWLR 2020).

1990s: Demand Management and Recognizing Aquifers as Storage

The 1990s marked a shift toward optimization of the system. Following Namibia's independence from South Africa in 1990, Windhoek's urban population grew at a rapid rate, but whereas previous decades were focused on increasing bulk water supply by constructing new water storage infrastructure, the 1990s saw the emergence of system optimization as priority as well as demand management (MAWLR 2020). In 1994, the city began introducing demand

TABLE 8F.1 Three-Dam System: Features

FEATURE	VON BACH DAM	SWAKOPPOORT DAM	OMATAKO DAM	THREE-DAM SYSTEM
River	Swakop River	Swakop River	Omatako River	
Year completed	1970	1977	1982	
Distance from Windhoek (km)	70	90	160	
Capacity (Mm^3)	48.56	63.48	43.50	155.54
Catchment area (km^2)	2,920	5,480	5,320	
Surface area at full supply level (km^2)	4.89	7.81	15.54	
95% assured yield (Mm^3)	6.5	4.5	2	20
Primary purpose	Water supply	Water supply	Water supply	

Sources: MAWLR 2020; Sirunda and Mazvimavi 2014; van Rensburg and Tortajada 2021; ICOLD 2020.

management strategies, including leak detection, public engagement, and the use of semi-purified effluent for irrigating gardens and public spaces, which successfully reduced potable water demand by 20 percent; but these measures did not sustain a reduction in demand beyond the 1996–97 drought (Taylor 2019; van Rensburg and Tortajada 2021).

During the 1996–97 drought, the government invested in feasibility studies for artificially recharging the city's groundwater resources, including first injection testing to establish proof of concept (Taylor 2019). By 2004, it was ultimately determined that a large-scale managed aquifer recharge (MAR) scheme using the Windhoek Aquifer was feasible and cost-effective. Given groundwater was less susceptible to evaporation, MAR offered a more resilient storage alternative than the surface reservoirs around the city. New laws and regulations were passed in 2005 to protect the recharge areas, and the first period of artificial recharge began in 2006. Between 2006 and 2012, a total of 2.83 million m^3 was recharged using direct injection in six boreholes, which brought the aquifer to its highest levels since the start of large-scale abstraction in the 1950s, but demand was still well above the sustainable yield (Murray et al. 2018).

2010s: Operationalizing WMARS

From 2015 to 2017, the area was hit by another severe drought and water crisis. In 2015, the Central Area received 197 millimeters of rain compared to the long-term average of 360 millimeters, and NamWater was expecting surface water dams to be empty by late 2016. During this time, the groundwater reserves in the Windhoek Aquifer, as well as direct potable reuse, emerged as the most feasible supply alternatives (van Rensburg and Tortajada 2021). After repeated requests, the Ministry of Agriculture, Water and Forestry mobilized funding through NamWater for emergency implementation of abstractions from the Windhoek Aquifer to draw on the reserves from the WMARS (Scott et al. 2018). Twelve additional boreholes were drilled, and the project came online in December 2016, which was about the time the three-dams system was expected to "run dry" (van Rensburg and Tortajada 2021). At the same time, direct potable reuse production capacity was increased, and the City of Windhoek put in place the first version (2015) of its Water Demand Management Strategy and Drought Response Plan.[1] By 2017, its public campaign to "Save Water" had achieved 33 percent reduction in water demand (Scott et al. 2018).

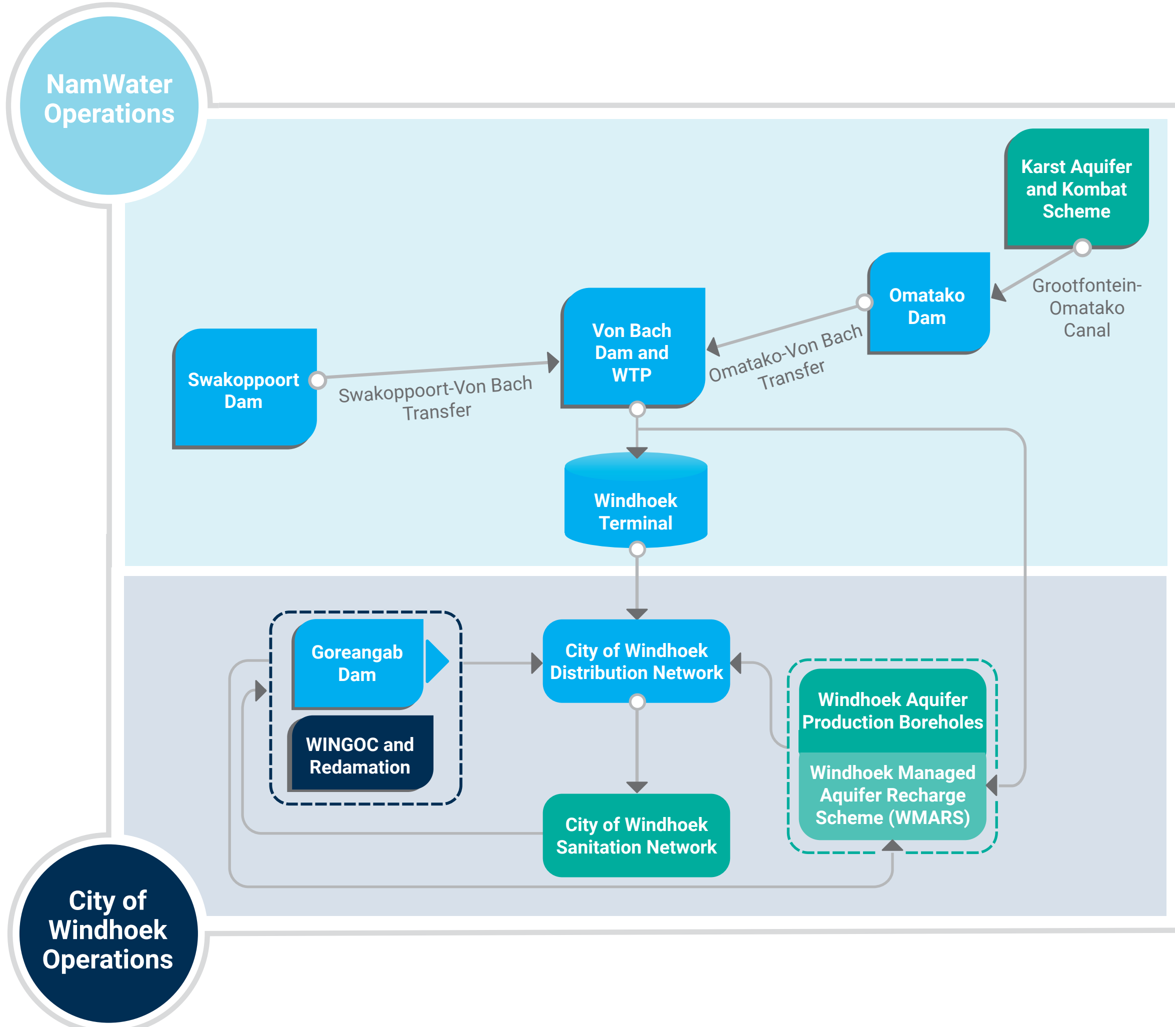
SOLUTION IMPLEMENTATION

Interconnected Storage Facilities

Windhoek manages its surface and groundwater conjunctively with measures across both natural and built storage types to reduce water losses due to evaporation and to increase the availability of freshwater during drought (figure 8F.2). Specifically:

- Water is impounded in three dams around the city to capture and store flows from the ephemeral rivers running through the interior of the country.
- Water is also transferred from the karst aquifer near Grootfontein north of the city to Windhoek via canals to Omatako Dam (Mapani 2005).
- Water in the Omatako and Swakoppoort reservoirs is transferred to the Von Bach Reservoir with a smaller surface area before it is treated and sent to the city.
- This water is comingled with water from boreholes in the Windhoek Aquifer and surrounding aquifers as well as recycled water from the New Goreangab Water Reclamation Plant—a larger, more advanced facility commissioned in 2002 (van Rensburg and Tortajada 2021).
- The Windhoek Aquifer is recognized as a convenient and resilient natural water storage facility with excess water "banked" underground as a buffer against drought. The scheme is recharged with treated water that is a 3:1 blend of dam water and reclaimed water (Murray et al. 2018). It is estimated that the WMARS could eventually store up to 71 million m^3 of water if deep aquifers are included (van Rensburg and Tortajada 2021; Zheng et al. 2021). The fully developed WMARS system is expected to have a recharge capacity of 12 million m^3 per year and an abstraction capacity of 19 million m^3 per year (Zheng et al. 2021).
- Water demand management is a key response mechanism for Windhoek in times of low water supply. An index based on percentages below average supply levels in the three dams is implemented with categorizations with varying degrees of severity, starting with calls on the public to reduce consumption in times of normal and slightly low supply levels, to enforced restrictions as the situation becomes more severe (City of Windhoek 2019).

FIGURE 8F.2 Elements of Windhoek's Water Storage System



Source: Original figure for this publication based on MAWLR 2020.
Note: WINGOC = Windhoek Goreangab. Operating Company; WTP = water treatment plant.

» For the dam water used to recharge the system, the City of Windhoek pays NamWater a cost recovery tariff; an additional charge (profit for NamWater) is then realized when the artificially recharged water is supplied by the city to customers (Murray et al. 2018).

Challenges

Windhoek is recognized globally for its innovation and leadership in urban water management under scarcity, but the city still faces a number of challenges to its water security. There are very real concerns about the ability of the water supply system to deliver service with high levels of assurance into the future given the trajectory of future demand growth. Virtually all of Windhoek's water supply options have been fully developed with the exception of the WMARS, for which there are plans to increase its capacity. The system also has a lot of complexity, and operating costs are high for its energy-intensive water transfer systems. Additionally, infrastructure aging and lack of preventative maintenance are a growing concern, considering much of the major bulk water storage and conveyance infrastructure is several decades old.

On the institutional side, while there have been efforts to adopt and operationalize IWRM principles, major gaps remain in the legal and regulatory framework with the national Water Resources Act not yet in force since its passage in 2013. According to most recent indicators on SDG 6, Namibia's degree of IWRM implementation is at 53 percent, which is roughly on par with the global average (54 percent). However, the indicators show that Namibia's IWRM implementation has declined in 2020 compared to 2017, when the level was recorded as 59 percent (UNEP 2021).

LESSONS LEARNED

- **Drought and water crises can spur innovation and galvanize action for important water resources investments.** Windhoek's water management story is one where severe droughts and subsequent water crises created an enabling environment for investing in costly and innovative solutions. For example, the drought of 2015–17 motivated the introduction of a new water demand management strategy and funding for the operationalization of the WMARS scheme before the anticipated "run-dry" date, putting in place plans that had been conceived several years before.
- **Spatial planning, including zoning, is key to protecting the quality of water stored in both built and natural systems.** The City of Windhoek took steps to locate certain water-using industries to an industrial zone in the northern part of the city to facilitate separation of harmful industrial effluents from domestic effluents, which can be reclaimed for direct potable reuse. These zoning decisions were also part of the solution to protect the recharge areas of the Windhoek Aquifer. Nevertheless, water quality remains an issue, particularly in the Swakoppoort Dam, as all wastewater runoff from the Windhoek and Okahandja areas end up in the Swakoppoort Dam's catchment. This issue is further exacerbated by the long retention time (storage is triple the mean annual inflow) and high evaporation rates. It remains imperative therefore for Windhoek to apply strict effluent standards and controls, in collaboration with all parties concerned.
- **Diversification of water sources and conjunctive management of different storage types make the system more flexible and resilient.** With water being sourced from boreholes, surface impoundments, inter-basin transfers, and wastewater reclamation, the City of Windhoek has diversified its supply of freshwater, and by managing the different sources and storage facilities as a system, is able to adjust its operations according to different supply conditions. During times of relative abundance, water from the three-dams system and water transfer schemes as well as water reclamation facilities can be "banked" underground for future use, and in drought years, when surface water facilities may fail, these reserves can be accessed.
- **In arid and semi-arid environments, "banking" water underground through MAR can significantly reduce evaporative losses in the water supply system.** In Namibia, just 3 percent of precipitation becomes runoff or recharges groundwater supplies, and evaporative losses from surface reservoirs and open conveyance infrastructure are enormous; in this context, underground storage offers a significant advantage in terms of securing water reserves, given there is virtually no evaporation.
- **Direct potable reuse is a scalable alternative water source in growing cities.** As the urban population grows, the supply of wastewater will also grow, so if wastewater can be reclaimed and treated to potable quality, it is a source that can be scaled as demand for water increases. In the case of Windhoek, the reclaimed water is treated to potable quality and can meet quality standards for injection at the WMARS. Investing in circular and resilient water systems can help cities save on capital investments and generate wider benefits to society (Delgado et al. 2021).

ENDNOTES

1 Versions 2 and 3 were put out in 2017 and 2019, respectively.

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ANNEX 8G. PAKISTAN: HYDROPOWER DEVELOPMENT IN THE JHELUM-POONCH RIVER BASIN

CASE STUDY BRIEF
Summary
Hydropower development in the Jhelum-Poonch River Basin is a valuable case study on how to minimize the impacts of water resources development through a systems-driven approach at the basin scale. The case study's context is familiar to many practitioners; master planning for the basin was completed and storage projects identified decades earlier without accounting for subsequent trade-offs between development and socio-environmental impacts. In this context, the application of a basin-wide planning approach before implementation offered the opportunity to take a step back and avoid "locking-in" the basin in a potentially unsustainable hydropower development modality.
Type(s) of water storage used
› Small reservoirs/retention structures
Water service(s) of storage provided
› Flow regulation
Water requirement(s) of storage met
› Water controlled for electricity generation › Water provision for ecosystem preservation and restoration

BACKGROUND

The Jhelum-Poonch River Basin is a transboundary river basin shared between India and Pakistan. It originates in the western foothills of the Pir Panjal Range of the Himalayas and descends steeply until it reaches the foothill areas where the gradient flattens out and the river widens as it is joined by several tributaries. The Poonch River drains into Mangla Lake, the reservoir formed by the Mangla Dam at the confluence of the Poonch and Jhelum rivers at an annual inflow rate of 794 m^3/s (Azmat 2015), but with high seasonal variability (IFC 2021a). This case study applies to the Jhelum and Poonch subbasins in the Upper Indus Basin (referred to here as "Jhelum-Poonch River Basin").

Hydropower and environmental conservation are the two main uses of the river. Irrigation is not a major water user in the basin because of the terrain, which makes it difficult to bring water from the river up to agricultural terraces. People rely on side streams for irrigating agricultural fields; however, withdrawals are negligible. Similarly, there is only negligible reliance on rivers for drinking and other domestic uses. The river does not have cultural or religious significance, and there is virtually no industrial use in the area. However, the river is an important source of livelihoods for people living in the area, with fishing and sand and gravel mining being the two key activities taking place along the river. All settlements in the area are connected to the national grid, and thus would indirectly benefit from increases in hydropower generation to the national grid (MPL 2014).

Hydropower surveys in the Jhelum-Poonch Basin were carried out by Pakistan's Water and Power Development Authority (WAPDA) from as early as the 1980s to identify potential projects for development (IFC 2021a). The hydropower plan emerging from these surveys considered potential facilities in the basin, including Gulpur, Sehra, Kotli, and Rajdhani on the Poonch River (IFC 2021a). While this plan recognized the hydropower potential of the basin, it did not include the area's ecological and socioeconomic picture when proposing project sites and specific designs for the facilities. Furthermore, several prospective hydropower projects were subsequently planned and offered to the private sector without considering larger planning scales and cumulative impacts and benefits.

All the hydropower projects planned for the Jhelum Poonch River Basin are run-of-the-river projects without large reservoirs. Nonetheless, reservoirs are still being created under the plan, however small their capacity, with impacts on the aquatic ecology of the river, including through habitat fragmentation and changes to the geomorphological profile of the river. The alteration to the natural sediment transport in the river is an additional expected impact. Plan implementation began in the 2010s with the financing of the Gulpur hydropower project. As described in this case study, the application of the basin-wide planning approach before project implementation offered the opportunity to revise (a) the project's initial design and (b) the existing plan to identify and then implement water storage solutions compatible with the Jhelum-Poonch River Basin's social and environmental values.

PROBLEM DEFINITION

This case study demonstrates how to balance two development objectives: the need to increase access to affordable, reliable, and renewable energy services, and the need to restore and retain natural systems of inherent value and significance.

Increase Access to Affordable, Reliable, and Renewable Energy Services

In the 2000s and 2010s, Pakistan experienced an energy crisis with acute power shortages, high costs of electricity, and high dependence on imported fossil fuels. As part of its reform process to improve the performance of the energy sector, Pakistan has sought to increase generation and transmission capacity, increase the penetration of renewable sources, and attract private investment to the sector. By the end of 2020, Pakistan was experiencing a power surplus thanks to new generation investments coming online and weaker than expected demand due to the COVID-19 pandemic (World Bank 2020).

Hydropower has had an important role in meeting the country's energy demands and greening the electricity sector. Total installed capacity is about 7.3 GW, dominated by Tarbela (3.5 GW), Ghazi Barotha (1.5 GW), and Mangla (1.0 GW). Pakistan has ambitious plans to increase hydropower capacity more than fivefold through 55 new projects that are at various stages of readiness, including 10 under construction

(Young et al. 2019). In one year, from 2019 to 2020, the share of Pakistan's electricity generated by hydropower increased from 25.8 percent to 30.9 percent (IFC 2021a). Hydropower development has been prioritized across the country, and development of the significant hydropower potential in the Upper Indus Basin (where the Jhelum-Poonch River Basin is located) is a major priority.

Restore and Retain Natural Systems of Inherent Value

The Jhelum-Poonch River Basin has significant biodiversity value. The warm-water river is rich in aquatic biodiversity and has been described as ecologically "highly sensitive" (IFC 2021a). At least 38 fish species have been found in the Jhelum-Poonch River Basin, including fish of very high commercial importance such as the endangered golden mahseer *(Tor putitora)*, which is a long-distance migratory species and whose largest and most stable population is found in the Poonch River (IFC 2021a). Due to this rich biodiversity and the economic importance of the fish found in the river, the entire length of the Poonch River in the area under Pakistan's control was declared as Poonch River Mahseer National Park in 2010 (IFC 2021a). However, activities such as illegal and unregulated sand and gravel mining and fishing are still taking place in the national park.

INSTITUTIONAL FRAMEWORK

Public sector agencies tasked with environmental management are key elements of the institutional framework. The responsibility for managing the river and river-dependent fish species within Mahseer National Park (where the Jhelum-Poonch River Basin is located) rests with the State Wildlife and Fisheries Department, which works closely with the Forest Department to manage the national park. The State Environmental Protection Agency has responsibility for protecting, conserving, and improving the environment and promoting sustainable development, and, in this capacity, regulates the development projects in the area (IFC 2021a). Various civil society organizations operate in the region, including the Himalayan Wildlife Foundation, which was a main proponent of the creation of Mahseer National Park.

Stakeholders concerned with the planning and delivery of hydropower projects are another key element of the institutional framework. Hydropower development in Pakistan is guided by the national Policy for Power Generation (2015), formulated by the Ministry of Energy (Power Division), and WAPDA's Vision 2025: Hydro Development Plan. Hydropower development is prioritized under the Policy for Power Generation through its aim to enhance the share of renewable energy resources and to encourage the development of indigenous resources.

Given fiscal constraints at the national level, WAPDA's Vision 2025 is strongly oriented toward the private sector. Private investments in the power sector are promoted by the Private Power and Infrastructure Board (PPIB) of Pakistan, which acts as a "one-window facilitator" on behalf of the government. The PPIB approves independent power producers, approves feasibility studies, and has a number of other functions related to facilitating private power development.

Hydropower development in the Jhelum-Poonch River Basin is regulated under the laws and regulations of the state government, which includes legislation enacted in Pakistan and adopted by the state legislature. The state government established the Hydro Electric Board in 1989 to facilitate hydropower development in the region, and later in 1995, it created its own "one-window facility," the Private Power Cell, to encourage private sector involvement in hydropower.

The license for the Gulpur hydropower project triggered the basin-wide approach described in this case study. It was awarded by the PPIB (acting on behalf of the state government) to Mira Power Limited, a special purpose vehicle under a build-own-operate-transfer scheme. Mira Power Limited signed a 30-year power purchase agreement with the National Transmission and Dispatch Company of Pakistan. Other stakeholders involved in the case study include the International Union for the Conservation of Nature (IUCN), involved in the preparation of the strategic environmental assessment (SEA), the IFC, and the Asian Development Bank as project financiers and, in the case of IFC, delivering advisory services.

THE EVOLUTIONARY PROCESS

Hydropower development in the Jhelum-Poonch River Basin presents a valuable case study on how to minimize the impacts of water storage development through

a basin-scale planning approach. This system-oriented approach differs from a more common approach to hydropower development that proceeds on a project-by-project basis and often considers environmental and social impacts, and related mitigation measures, after a specific project has been selected or agreed to a given operational regime. To implement this planning approach, an SEA and a cumulative impact assessment (CIA), including a holistic environmental flow assessment (EFA), were conducted, along with the development of the Strategy for Sustainable Hydropower Development in the Jhelum Poonch River Basin and stakeholder engagement throughout these processes.

Strategic Environmental Assessment

Starting in 2012, the Government of Pakistan and the IUCN jointly undertook an SEA for hydropower in the Upper Indus Basin region. The SEA sought to understand the state of hydropower planning in the region; assess the potential environmental and social risks and benefits associated with existing hydropower plans; suggest alternatives if necessary; and assess the institutional and policy constraints to environmentally and socially responsible hydropower development in the region (NCEA 2021). The SEA was regional in scope, thus looking at the risks and opportunities of all potential hydropower developments not just in the Jhelum-Poonch River Basin, but in the entire region. The SEA took the form of an ex-post assessment based on the collection of 62 existing or proposed projects that made up the government's hydropower development plan. The SEA followed eight steps (NCEA 2021):

Step 1: Define and categorize the proposed projects as listed in the existing regional hydropower plan

The step of mapping and identifying hydropower projects in different stages of development in the basin made use of information from public and private resources readily available to the public.

Step 2: Outline the structural design features of a selection of proposed projects of differing generation capacity

This step characterized the main features of different types of projects proposed in the regional hydropower development plan. This includes differentiating between conventional storage of water impounded by a dam or run-of-the-river projects. Projects were also characterized by considering their type of intake weir, penstocks, powerhouse, and existence of/proximity to access roads and transmission lines.

Step 3: Define generic drivers of potential environmental and social impacts

Based on the different types of projects identified in step 2, the SEA also listed a generic set of drivers of environmental and social impact. For example, the type of diversion structure and the extent of diversion of water were identified as major drivers of environmental impacts. In addition, activities related to construction were also drivers of impacts, such as gaseous emissions and solid waste.

Step 4: Investigate links between drivers and actual potential impacts

Under this step, the expected effects from projects of different generation capacities were described. Given the diversity of hydropower projects and the site-specific nature of all projects, environmental and social impacts are varied and difficult to generalize. In most parts of the world, impacts are typically differentiated between small and large hydropower based on installed capacity. In Pakistan, there is a demarcation of hydropower plants (HPPs) above and below 50 MW based on a very broad and general definition of expected environmental impacts from project, which was utilized in the SEA to categorize drivers of impacts.

Step 5: Define cumulative impacts

This was a critical step of the SEA, which was informed by the principle that the magnitude of environmental and social impact drivers can be mapped, and that there may be cumulative impacts that should be taken into account when decisions are made about the implementation of the development plan. Under this step, the SEA examined the environmental and social risks associated with planned hydropower development on specific stretches of rivers and streams. Based on the geographical locations and potential cumulative impacts expected from hydropower development, river and stream sections are delineated into cumulative impact zones and thus ranked based on their susceptibility to cumulative impacts.

Step 6: Characterize environmental and social baseline conditions

For the purpose of the SEA, the condition of the environmental baseline in relevant rivers and streams was represented by fish, which are the most easily studied aquatic organisms. The diversity of the fish species was used to determine the ecological importance of nine designated ecological zones of the region. The following parameters were used: fish diversity; economic importance of fish; conservation importance of fish; and classification as protected area. In addition, the connectivity to upstream and downstream ecosystems was taken into consideration to assess the ecological importance of each zone. The social importance was characterized through three sets of indicators related to fishing, sand and gravel mining, and tourism potential. Other aspects such as cultural and religious importance and use of water for drinking and resettlements were not considered relevant for this specific case. For each set of indicators, the SEA assessed the sensitivity of each river segment to development.

Step 7: Rank projects according to their cumulative impact potential

This step combined the results from steps 5 and 6. It superimposed cumulative impact zones onto environmentally and social sensitive river/stream segments, thus allowing for each project contained in the hydropower development plan to be ranked according to its overall cumulative impact potential.

Step 8: Inform and influence decision-making around hydropower development in the basin

The SEA and related ranking of projects based on their cumulative impact allowed the state government and project developers to (NCEA 2021):

- Clearly understand that the Poonch River was the area of most concern from both an ecological and socioeconomic standpoint.
- Fully understand cumulative impacts of large hydropower developments and their implications.
- Collaborate for the first time on hydropower coordination in the basin and examine the benefits of coordinated mitigation measures.
- Identify opportunities for revising the region-wide hydropower plan.

The SEA clearly indicated that the Jhelum-Poonch River Basin is an area of ecological and socioeconomic importance. Keeping in mind the high ecological sensitivity of the Jhelum-Poonch River Basin, the SEA recommended that all the hydropower projects planned in the Jhelum-Poonch River Basin should use holistic approaches to determine downstream environmental flows. This recommendation was essential in guiding further development in the basin and the related CIA.

Cumulative Impact Assessment and Environmental Flow Assessment

The basin-wide SEA was followed by a CIA including a holistic EFA to inform hydropower development in the Jhelum-Poonch River Basin. The CIA adopted a strategic hydropower planning approach, considering up to five hydropower developments on the main stem of the Poonch River. At the time of the assessment, designs were complete only for two projects while the other proposed projects were at pre-feasibility stage. This presented significant opportunities for the CIA to suggest modifications to the existing designs and pre-feasibility considerations. The CIA was conducted following IFC guidelines, shown in figure 8G.1, with each of the steps described in more detail.

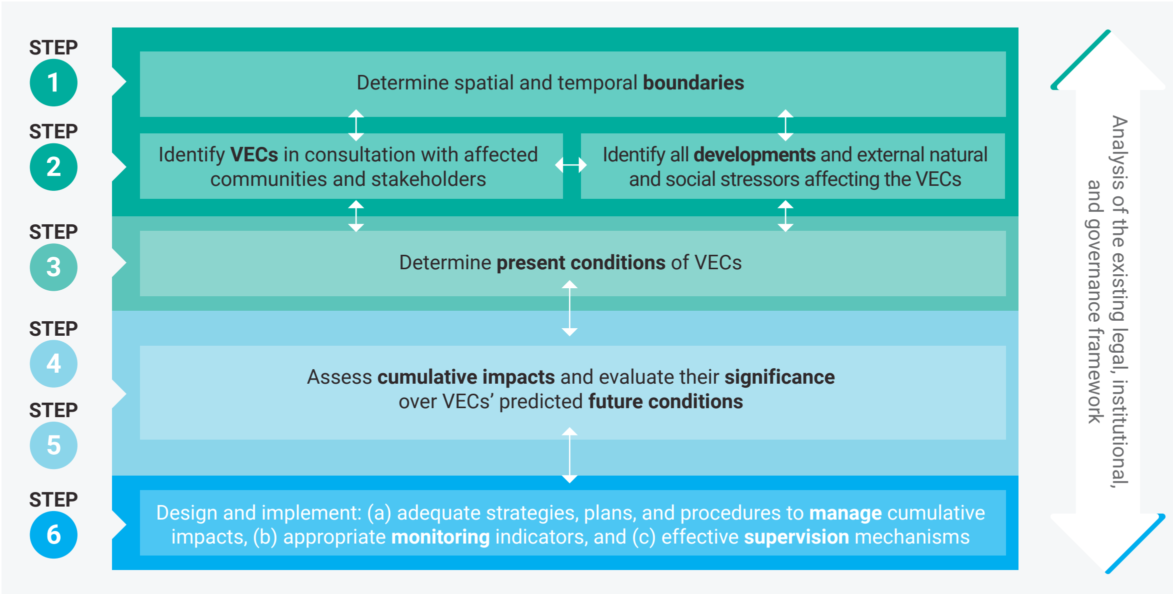
Steps 1 and 2: Define study area and identify VECs

These steps involved the delineation of the study area, and the identification of valued ecosystem components (VECs), which are the fundamental elements of the physical, biological, or socioeconomic environment that are likely to be the most sensitive to the impacts of a proposed project or the cumulative impacts of several projects (IFC 2013). The study area was identified as including the Jhelum-Poonch subbasin managed by Pakistan. The CIA also considered past, existing, and planned projects in the study area. The VECs selected for this project were: (a) surface water quality and quantity; (b) sediment; (c) resident and migratory fish species; and (d) landscape (Cardinale, Lazurus, and Alonso 2018). The selection of VECs was the result of an extensive stakeholder engagement exercise and expert consultation, to avoid expanding the CIA beyond issues relevant to the study area.

Step 3: Determine VECs baseline

To determine the VECs baseline and inform the subsequent EFA (step 4), extensive surveys were conducted. Aquatic surveys helped quantify the status of fish populations in the river and its tributaries. Settlement-level and sampled surveys were conducted to obtain information on fishing and sand mining, which are known to influence surface water quality and fisheries sustainability. Hydraulic and geomorphological surveys were

FIGURE 8G.1 IFC Guidelines for Conducting Cumulative Impact Assessment



Source: IFC 2013.
Note: VEC = valued ecosystem component.

also carried out to determine baseline characteristics of important indicators, such as fish spawning grounds or exposed cobble bars. Geomorphological surveys of river morphology and bed sediments were used to generate hydraulic relationships. Ecological field surveys included baseline studies on fish, macroinvertebrates, macrophytes, and riparian vegetation and were used to define baseline ecological conditions and guide the choice of indicator species (Brown et al. 2019). Surveys were augmented with analysis of historical and published data.

Steps 4 and 5: Cumulative impacts assessment

The CIA was carried out in two steps. First, the impact of the Gulpur project on VECs at the basin-wide level was studied (step 4). Second, the impact of additional planned and foreseeable hydropower projects on the VECs in the basin was examined (step 5). The two steps are described together as they were based on the same EFA model.

The Gulpur project was the first hydropower project implemented by Pakistan to undertake a comprehensive EFA. The objective of the EFA was to evaluate the pre-project condition of the Poonch River from upstream of the project site to the Mangla Dam and how the condition of the river could change under different project designs and operational regime scenarios. The EFA used the Downstream Response to Imposed Flow Transformations (DRIFT) model and studied the economic impact on power generation and ecological impact of key species with different levels of minimum environmental flow (Brown et al. 2013). The early EFA report was based on an initial design, Option 1, and later revised to examine alternative project designs and was included in the final version of the CIA.

The EFA for the Gulpur project involved four activities, supported by an extensive stakeholder engagement process (Brown et al. 2019):

- *Scenario selection*. Scenarios were developed by combining various permutations of the following factors: (a) environmental flow releases, (b) turbine options, (c) levels of river protection, (d) barrier effect on sediment supply and fish migration, and (e) mode of operation (baseload versus peaking).
- *Site selection*. Four environmental flow sites were selected for the assessment, located upstream of the reservoirs, between the weir and the tailrace, 7 kilometers downstream of the tailrace and 16 kilometers downstream of the tailrace.
- *Knowledge capture*. In this step, knowledge around drivers and outcomes was synthesized through a set of indicators for each of the four environmental

flows sites (table 8G.1). A set of driving hydrological indicators (e.g., flood volume, dry season duration) and responding habitat and biota indicators (e.g., active channel width, depth of pools, fish species) were identified. The habitat and biota indicators are those reported in the EFA. The links between driving and responding indicators for the Poonch River restricted the linkages to those that were deemed most meaningful and could be used to predict the bulk of the likely responses to a change in the flow or sediment regimes of the Poonch River (Brown et al. 2019). With the important links agreed, experts described the nature of the links as response curves, which were then inserted into the DRIFT model.

» *Analysis*. For each scenario, the DRIFT model simulated (a) an overall ecosystem condition for each river reach using an integrity range from A (natural) to F (highly degraded), (b) a time-series of change for the 20 habitat and biota indicators, and (c) cost of power generation.

The EFA model was then expanded to also consider the impact from four additional planned projects. To inform the simulation, scenarios were developed comprising three levels of hydropower project development, two levels of management of the downstream river reaches and key tributaries, and variations on HPP operations, including sediment flushing and peaking versus baseload power generation (IFC 2021b). Based on an assessment of changes in key indicators for each scenario, the DRIFT model predicted the overall river condition for 30 years into the future starting from 2012. The basin-wide simulation demonstrated that a gradual increase in the number of hydropower projects in the study area would lead to a decline in sand and gravel availability in rivers, an increase in the availability of cobble and boulders, a reduction in habitat diversity, and knock-on effects on riverine ecosystems.

The EFA concluded that the flow changes from the proposed projects, without protective measures, would severely impact the river. Some 87 percent of the Poonch River between Parnai hydropower project and the Mangla Reservoir would be affected with some of the river lost to inundation and more impacted by reduced dry season flows (MPL 2014). The EFA also concluded that development of all five proposed facilities would also lead to very significant negative impacts for the aquatic biodiversity in the river.

TABLE 8G.1 Indicators in DRIFT Model Simulation for the Poonch River

GEOMORPHOLOGY	Active channel width
	Area of silt/mixed deposits
	Area of cobble bars
	Median bed sediment size (armoring)
	Depth of pools
	Area of second channels and backwaters
WATER QUALITY	Nutrients
	Temperature
ALGAE	Periphyton biomass
RIPARIAN VEGETATION	Dry ban trees and shrubs
MACRO-INVERTEBRATES	Simulidae
	EPT biomass
FISH	Pakistan labeo
	Mahasheer
	Twin-banded loach
	Kashmir catfish
	Garua bachwaa
	Snow trout
WILDLIFE	Fish-eating wildlife
	Wildlife water needs
	Riverine insectivores

Source: Based on IFC 2021b.
Note: The breadth of indicators included in the DRIFT model simulations for the Jhelum-Poonch River Basin highlights the importance of adopting a multi-disciplinary and basin-wide approach. EPT = Ephemeroptera, Plecoptera, and Tricoptera.

Step 6: Implementation strategies

The final step of the CIA entailed designing and implementing strategies to manage cumulative impacts, monitor indicators, and establish supervision mechanisms. This resulted in the creation and implementation of a biodiversity action plan to ensure a net gain of biological values for which the critical habitat was designated. This also included putting in place a strong watch-and-ward system to minimize threats, such as illegal and unregulated fishing, to the ecological integrity of the river and supporting the captive breeding of vulnerable fish species (IFC 2021a). The plan also covers capacity building of the State Fisheries and Wildlife Department and awareness raising among the communities.

Sustainable Hydropower Development Strategy

The SEA and CIA served as a foundation for the development of a strategy for sustainable hydropower development. The strategy was developed through a multi-stakeholder engagement process to bring in a broader focus and include social and policy dimensions.

Compared to the previous steps, the strategy takes a step back to provide a basin-wide roadmap for implementing sustainable hydropower projects, with its recommendations covering aspects related to project impacts and basin-wide planning and available options, but also broader policy issues around hydropower sector regulation. To inform the strategy, six technical studies were conducted: (a) summary of physical conditions of the basin; (b) sediment audit; (c) zones of ecological importance; (d) zones of socioeconomic importance; (e) impacts of HPPs on sediment, geomorphology, socioeconomics, and other HPPs; and (f) assessment of cumulative HPP impacts on the ecology of the basin (DRIFT modeling).

Through this comprehensive approach, the strategy provides an assessment of the overall ecosystem integrity for each environmental flow reach under different scenarios. Scenarios were generated by combining three levels of hydropower project development and two levels of management of the downstream reaches and operation regimes, for a total of six scenarios which were then compared with baseline conditions (table 8G.2).

The scenario analysis was complemented by a policy and regulatory assessment. This assessment was conducted through stakeholder workshops and a review of lessons learned from the implementation of earlier projects. The assessment provides recommendations for governments on regulatory and policy reforms (including requirements for sediment monitoring and environmental impact assessments), protected areas, reservoir management and operation, inclusion of environmental costs in project tariffs, and reduction of impacts from transmission lines on terrestrial ecology, among others.

For hydropower developers, the assessment provides guidance on project designs that better balance power generation with environmental needs and that maximize synergies with other projects, preparation of biodiversity action plans, increasing capacity to manage environmental impacts and sediments, as well as practical recommendations on implementation, among others.

Stakeholder Engagement

Stakeholders—defined as groups or individuals that can change or be affected by the project's outcome—were involved through an extensive identification and consultation process. Institutional stakeholders included

TABLE 8G.2 Scenarios Assessing Ecosystem Integrity

LEVELS OF HYDROPOWER PROJECT DEVELOPMENT	Existing or under-construction projects
	Committed projects, for which detailed engineering is advanced and a tariff application has been submitted/approved by the regulator
	Planned projects for which a feasibility study has been prepared
MANAGEMENT LEVELS	"Agreed": meaning that they incorporate management provisions agreed between the regulators/government and the project developers
	"High": meaning that more stringent environmental protection than those "agreed" are applied (i.e., higher environmental flow releases)

Source: IFC 2021a.

federal entities such as WAPDA, the National Electric Power Regulatory Authority, the Pakistan Environmental Protection Agency, and autonomous entities at the provincial level, such as the energy and power departments and their related sub-departments, fisheries and wildlife departments, provincial environmental protection agencies, and mining departments. Additional institutional stakeholders consulted included hydropower owners and developers by creating a Hydropower Developers Working Group, international development institutions, and nongovernmental organizations (NGOs). Stakeholder consultations with local communities were essential to capture and document knowledge with regard to river ecosystem and its functioning, and to document communities' dependence on river resources (mining, fisheries). Community-level consultations were held separately with women and men in 11 villages to inform them about the project, to record their input, and to address their concerns (Cardinale, Lazurus, and Alonso 2018), and community wardens were deployed to monitor the river. This multi-stakeholder engagement process was conducted throughout the strategic analysis and project construction. Notably, in 2015 and 2018, a set of multi-stakeholder workshops were held to develop and discuss the underlying methods and results that underpin the Strategy for Sustainable Hydropower Development in the Jhelum-Poonch River Basin. Stakeholder engagement is expected to continue throughout the project life cycle.

Summary of the Planning Approach

In summary, the planning approach employed in the CIA and EFA followed three main principles to reveal improved alternatives and designs, and to minimize impacts from water storage development. First, the approach was multi-objective. It considered more than 20 indicators well beyond the benefits arising from hydropower production. These included water quality (temperature, nutrients), geomorphology (channel width), fish, algae, riparian vegetation, and wildlife. The careful formulation and inclusion of multiple objectives in a single decision framework helped quantify trade-offs and the ability of alternative options to fulfil environmental and social objectives. Second, the analysis was multiuse. When examining water storage options along a river, planners are typically only concerned with water quantity (i.e., river flow regime). However, rivers have multiple uses which need to be taken into account. In this case, the approach covered multiple uses, including water consumption, water quality, fishing, mining (sand and gravel, and cobble and boulders), and sediment budgets. Finally, the approach employed in the CIA and EFA was multi-stakeholder and included federal and provincial entities, local communities, local and international NGOs and developers. In the end, the findings and decisions from the CIA and EFA were then incorporated into the Strategy for Sustainable Hydropower Development in the Jhelum-Poonch River Basin, taking lessons about other water users and needs back into the overall strategy for hydropower development.

SOLUTION AND IMPLEMENTATION

The multipronged planning approach influenced decisions at the project and planning level in the Jhelum-Poonch River Basin.

Project Scale

At the project scale, it resulted in changes to the proposed design and operation of the Gulpur hydropower facility before it was commissioned in 2020. The results of the EFA underpinned the following design and operational considerations:

- Operate the hydropower facility as a baseload power generation (thus forgoing peaking power generation);
- Relocate the weir closer to the powerhouse;
- Release a minimum flow of 4 m^3/s;
- Select different turbines from those originally planned to allow for greater flexibility under low-flow conditions; and
- Establish a fish hatchery and use it to stock the river reach downstream of the hydropower facility to allow for sustainable artisanal and recreational fishing.

System Scale

At the system scale, it provided a framework to guide water storage management and development in the basin. First, the analysis cautioned against any further water storage development in the basin (MPL 2014). Second, the analysis resulted in the creation of a basin-wide biodiversity action plan to address basin-level protection of wildlife, under the jurisdiction of the State Fisheries and Wildlife Department. The biodiversity action plan contains a set of management interventions, with associated financial arrangements, to achieve high levels of ecosystem protection in the Poonch River National Park. The implementation of the plan is still in the early phases, but it is already showing positive results (IFC 2021a). Finally, the analysis resulted in the creation of a framework to guide sustainability actions in the basin (IFC 2021a).

LESSONS LEARNED

» In many cases, trade-offs can be better managed at larger planning scales, from individual dams to the whole basin. Systems thinking reveals improved alternatives and translates into more and better services from water storage. Without the basin-wide approach, the biodiversity action plan would have never been developed and opportunities to achieve net gains in biodiversity value would have never been identified.

» Basin-wide conceptual design and prefeasibility help identify impacts and plan for mitigation early. The SEA for hydropower development in the Upper Indus Basin prepared by the IUCN helped stakeholders identify impacts and plan for mitigation early. Specifically, the SEA highlighted the importance of undertaking a holistic EFA before proceeding with any hydropower development in the basin.

» Holistic assessments of environmental flows are key instruments to identify operational regimes capable of meeting multiple objectives. Application of holistic EFA undertaken as part of an environmental and social impact assessment was crucial to screen and optimize alternatives and analyze cumulative impacts on ecosystems. In this case, quantitative what-if analysis of environmental flows paired with careful consideration of impacts on threatened fish and river ecosystem influenced the planned turbine design, weir location, and operational regime of the project. Capacity development of local consultant firms, developers, and government was also crucial to understanding the importance of EFA, which would later come into play when discussions were underway on cascade management.

» Development of basin-wide sustainability strategies helps integrate management measures over the long term. Long-term sustainability of hydropower requires implementation of measures covering biodiversity, erosion control, sediment management, stakeholder engagement, data collection and curation, livelihood and assessment and management.

» To confront the escalating commitment to an unsustainable existing master plan (lock-in), planners need to routinely adopt basin-scale assessments aided by decision support systems and regularly update them.

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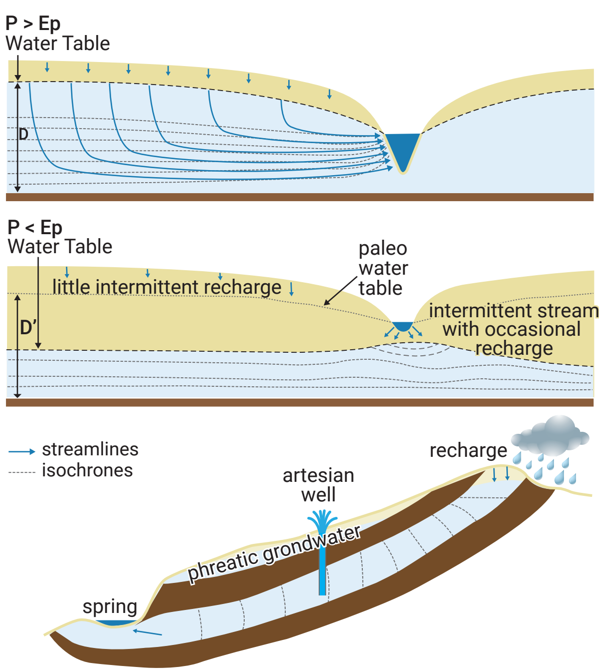
WATER STORAGE GLOSSARY 9

This glossary provides definitions of types of water stores and water storage systems discussed within the report. **A note to users: It does not intend to be exhaustive.** Many of the terms defined can have a range of alternate definitions depending on the region or sector in which they are used. This glossary does not endeavor to settle these differences, but rather attempts to provide broad definitions or types of storage and storage systems, to help familiarize the reader with the range of water storage options available.

Aquifer: An aquifer is a geologic formation that can store and yield water. There are two main types of aquifers: unconfined and confined (figure 9.1). Confined aquifers are under pressure due to an impermeable layer above the aquifer. The groundwater located in aquifers can be classified as fossil (ancient) and non-fossil (young), depending on the age.[1] High permeability aquifers can be sources of water for human usage if well managed.

FIGURE 9.1 Aquifer Types



Source: Bierkens and Wada 2019.
Note: Examples of groundwater systems: (a) aquifer in humid region (P > Ep) with a draining groundwater system; (b) aquifer in semi-arid region (P < Ep); (c) confined aquifer system. Groundwater in (a) is renewable and in (b) and (c) is non-renewable (Bierkens and Wada 2019). P = precipitation; Ep = evapotranspiration.

Dam: Dams are artificial barriers built for impounding or diverting the flow of water. The volume of water held back by a dam, on the upstream side of the dam, is the reservoir (see Reservoir). Large dams are typically defined as structures greater than 15 meters in height from base to crest or structures between 5 and 15 meters that impound reservoirs with a capacity of 3 million cubic meters or more (ICOLD 2003). There are two main types of dams: concrete dams and embankment dams (made up of earth or rock fragments). A weir is a low-head dam across the width of a river and is used primarily to raise the water level.

Dry dam[2]: Dry dams are constructed for the purpose of flood control and are intended to allow the river to flow freely during normal conditions.[3] Dry dams are built across the floodplain with a bottom outlet to let the main channel flow through, while during flooding it holds back excess flood volume and attenuates the volume to manageable levels for downstream areas (Poulard et al. 2010). By throttle effect, dry dams reduce the peak outflow and delay the peak discharge; however, the mitigated flood wave lasts longer. In some specific cases, the mitigated but delayed peak may become concomitant with the peaks of other contributions, hence increasing the flood hazard downstream (Poulard et al. 2010). The dam height can be often limited by cost and topographical features; the impact of the dam on downstream river environment can be reduced by adjusting the bottom outlet dimensions (Poulard et al. 2011).

Flood and diversion channels: Flood control channels or diversion channels are natural or built basins, which let water flow in when a flood occurs, and eventually drain into a river or other body of water.[4] The diversion system could divert floodwater (excess water flow) to a downstream section of the same river; to nearby tributaries within or outside the basin; or to retention areas for temporary storage (Gopalan et al. 2021). Typically, diversion channels are built around communities or economic centers to prevent extensive flood damage. Flood control channels run below the street levels of some larger cities. In rural settings, diversion canals can function as both floodways and irrigation channels.

Floodplain: A floodplain is a sedimentary plain of low relief bordering a river channel, constructed by various sedimentation processes and inundated to some extent by some annual floods in the current hydroclimatic regime of the river's drainage basin (Dunne 2022). During floods, floodplains essentially increase the storage or carrying capacity of the river. Floodplains can reduce the impact of erosion downstream by slowing the speed of floodwaters. The shape, size, and composition of any floodplain will determine how effective it is at storing and slowing floodwaters (Meitzen 2018). The shape and nature of a floodplain may change over time as the main channel of a river naturally migrates through erosion and accretion, affecting how and where excess water may first overtop the banks of the river during a flood event.

Glacier: "*A glacier is a large, perennial accumulation of crystalline ice, snow, rock, sediment, and often liquid water that originates on land and moves down slope under the influence of its own weight and gravity*" (USGS n.d.). About three-quarters of earth's freshwater is stored in glaciers, but only around 3 percent of the glacierized area is of direct importance to human settlements, providing water for irrigation, industry, hydropower, recreation, and domestic supplies.[5] The stored water volume of glaciers varies seasonally: cold seasons promote surging (mass gain) while warm seasons promote retreating (mass loss) and melting. The volume of glaciers can change at different time scales: sub-seasonal, sub-daily, multi-year, and decadal, and changes also in response to climate change (IPCC 2013). There are several categories of glaciers: mountain glaciers, valley, tidewater, piedmont, hanging, cirque, ice aprons, rock glaciers, ice caps, icefields, ice streams, ice sheets, and ice shelves (NSIDC n.d.). Mountain glaciers comprise 85.2 percent of the world's glaciers (Qin et al. 2021) and are those glaciers on the mountain slope that end in the middle before approaching the main river. Those at higher elevations in the mid-latitudes are particularly sensitive indicators of climate change.

Haffir (or hafir) is an Arabic word for ponds (FAO and UNEP 2015) and relates to a water harvesting method that involves small lakes constructed in low-lying areas to allow water to be stored during rainfall events (Mohamed-Ali, Luster-Teasley, and Nzewi 2009). Haffirs are extensively used in Africa, including Sudan and Tanzania, among others. Considerations for when a haffir is the selected option of water harvesting (FAO and UNEP 2015):

- Catchment area to capture the rainfall with collection or feeding channels to collect and convey the runoff to sedimentation basin
- Sedimentation basin to hold the runoff for a specific time and allow sediment particles to settle before entering the reservoir
- Inlet structure to allow the water from sedimentation basin into the reservoir
- Reservoir to hold the entire quantity of water for dry season use
- Intake for the pumping system
- Delivery or distribution pipeline systems to the cattle troughs
- Cattle troughs for both small and large stocks
- Overflow to convey and direct excess water to downstream location
- Embankment
- Perimeter fence to protect the reservoir by blocking free access by people and livestock
- Additional elevated reservoir where direct pumping supply to the troughs is not enough (optional)

In-field storage refers to water storage on farmland, either below or above ground, in ditches, canals, water courses, tanks reservoirs, lakes, and ponds. This includes in-field water harvesting solutions (Nyamadzawo et al. 2013), using agricultural fields as storage, such as paddy fields, among others. This is sometimes also called "on-farm" storage (Sahoo et al. 2021).

In-stream storage refers to water storage structures on rivers that alter natural flow regimes by storing, diverting, regulating, confining, obstructing, or directing the flow. These can include dams, weirs, canals, navigation locks, floodgates[6] (including those at the freshwater/

estuary interface), culverts, levee banks, erosion control structures in riverbanks (Garanaik and Sholtes 2013), and causeways.[7]

In-system (canal) storage: In-line or in-system storage refers to storing water in the main irrigation canal. Canal storage can be used to improve existing operational activities in the irrigation system, including by serving as night storage and/or flood attenuation. Downstream control is most suitable for a canal with night storage; if the canal also has to convey floods, additional upstream target levels will be needed. A mixed control system could be more appropriate for canals with night storage and for those that must convey floods (Schuurmans, Brouwer, and Wonink 1992).

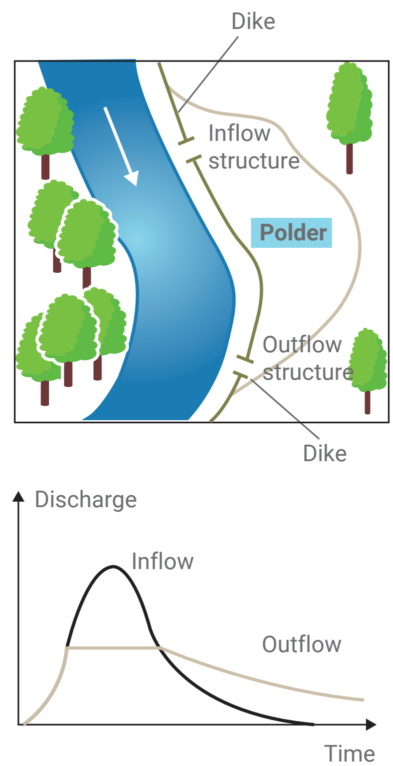
Lake: A lake is a type of natural reservoir of the Earth's surface water. A lake is a lentic (non-flowing) system where surface-water runoff (and potentially groundwater seepage) has accumulated in a low spot, relative to the surrounding countryside. The water entering a lake comes in faster than it exits, either via outflow in a river, seepage into the ground, or by evaporation. Different from ponds, lakes can store greater amounts of water. Lake water levels, especially in endorheic lakes (with no river outflow), are very sensitive to changes in the water balance (Wang et al. 2018). Historically, lakes have been used for numerous functions, such as flood control, biodiversity, climate change mitigation, river flow regulation, hydropower supply, and water purification and storage.

Landscape: Landscapes can modulate the influence of climate on water availability (Guswa, Hamel, and Dennedy-Frank 2017). The water storage capacity of the landscape refers to the ability to retain water during times of excess precipitation so it can be available during times of water scarcity and can mitigate the impacts of flood risks. The storage capacity of a landscape depends on the prevailing soil and vegetation types, especially their root systems. Consequently, management practices that contribute to perennializing the landscape, for example, winter cover crops or living mulches, may increase the effective storage capacity by increasing the mean effective rooting volume, if evapotranspiration from the plantings can be adequately minimized (Baker, Griffis, and Ochsner 2012). These practices are also thought to increase soil organic matter (Sainju, Singh, and Whitehead 2002), which is positively correlated with water-holding capacity (Hudson 1994; Baker, Griffis, and Ochsner 2012). A type of landscape, forests can help with the provision of green water, erosion control and regulation of sediment and nutrient transport in waterways, if managed accordingly (Filoso et al. 2017).

Paddy fields: Paddy fields consist of a field flooded with water for growing rice. While about 90 percent of the world's 160 million hectares of paddy fields are in Asian countries, mainly in monsoon regions, paddies are also seen in North America and Africa, including in dry regions (Watanabe 2018). Paddy fields are flooded naturally or artificially during rice production period. In the case that paddy fields are kept submerged artificially, hydraulic structures are often required, as are drainage systems.

Polder: Polders are retention areas alongside water bodies into which flood waters from the main river channel are diverted, in order to cap peak discharges and reduce downstream flood water levels (Mawandha, Wignyosukarto, and Jayadi 2017) (figure 9.2). An area becomes a polder

FIGURE 9.2 Polder



Source: Adapted from Bornschein and Pohl 2018.

when it is separated from the surrounding hydrological regime in such a way that the inside water level can be controlled independently of the surrounding regime (Mawandha, Wignyosukarto, and Jayadi 2017). This condition can be accomplished by various combinations of drainage canals and dikes (levees) (Luijendijk, Schultz, and Segeren 1988). Another common type is the dry polder, a reservoir accompanying dry drams with the sole function of serving as flood-control reservoirs. Dry polders, based on their storage volume and construction design, could be converted into wet polders and operated to also alleviate drought conditions (IP 2019).

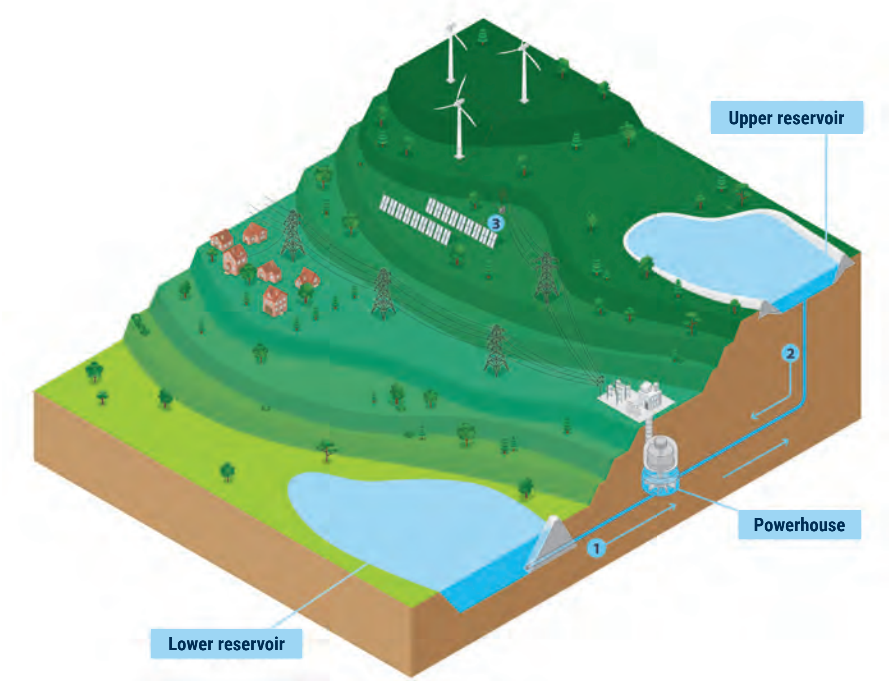
Pond: Ponds are lentic water bodies that can store water in smaller amounts than lakes. They are generally less than 2 hectares in size, shallow (less than 3 meters in depth), and are sometimes dominated by aquatic plants (Seetha and Chandran 2020). Ponds can be permanent or ephemeral, that is filling briefly during rain events and then drying out.

Pumped storage hydropower: A pumped storage hydropower facility generates hydroelectric energy by using water that has previously been pumped from a lower source to an upper reservoir (figure 9.3). Pumped storage facilities can be closed-loop or open-loop. Closed-loop facilities are off-river with no significant natural inflow of water to either reservoir. Open-loop facilities have upper or lower reservoirs that are continuously connected to a naturally flowing water feature.

Some open-loop systems can have significant natural inflows to the upper reservoir, such that some electricity may be generated without pumping. Pumped storage hydropower facilities, often called "water batteries," account for over 94 percent of installed global energy storage capacity and supports power grid stability (IHA 2018). While a net user of electricity, pumped storage hydropower generally works by pumping when electricity prices are low and generating when electricity prices are higher.

Reservoir: A reservoir is an artificial lake or body of water created by artificial barriers or dams. A reservoir can be formed in the river, as when impounded by a dam, or off-stream with surrounding embankments. A reservoir is typically considered large when its storage capacity exceeds 1 million cubic meters (ICOLD 2003).

FIGURE 9.3 Closed-Loop Pumped Storage Hydropower



1 During periods of low demand reflected by lower prices, renewable energy such as wind and solar is used to pump water uphill.

2 When demand increases, water from the upper reservoir runs downhill through the turbines to produce electricity.

3 Pumped storage combined with variable renewable energy can provide reliable, dispatchable and low carbon electricity to domestic and industrial consumers.

Source: IHA 2018.

Residence time: Refers to the average time that water spends in a given volume/space. The age, or residence time, of water is a fundamental descriptor of catchment hydrology, revealing information about the storage, flow pathways, and source of water in a single integrated measure (McGuire et al. 2005). The residence time (or distribution of residence times) of water draining a catchment not only has important implications for flow pathways and storage, but for its water quality, since many biogeochemical reactions are time-dependent (e.g., Hornberger, Scanlon, and Raffensperger 2001; Burns et al. 2003; McGuire et al. 2005).

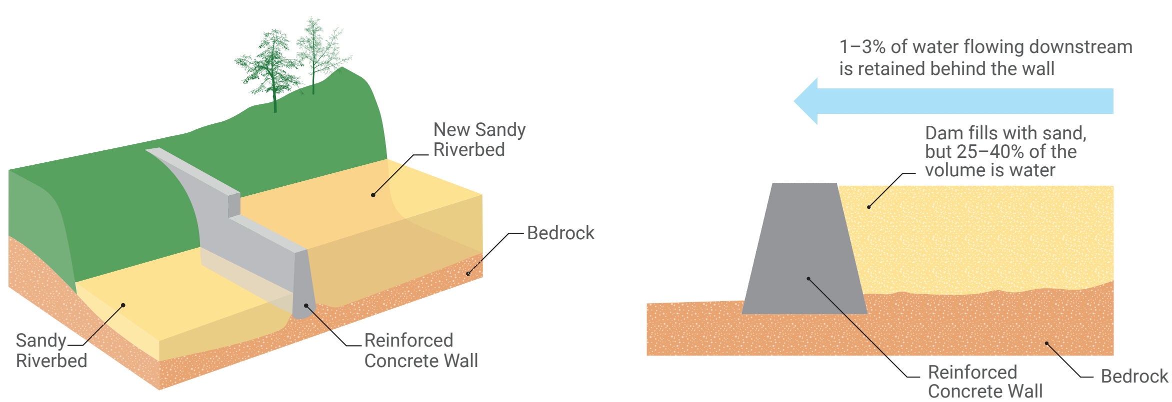
River: A river is *"a large natural flow of water that crosses an area of land and goes into an ocean, a lake, etc."*[8] Rivers in total can account for 0.6 percent of the total freshwater available on Earth, although they are the smallest water reservoir, after lakes and swamps (Bralower and Bice n.d.). Rivers can be formed by rainfall or snow melting and can be permanent or seasonal (ephemeral).

Sand dam, also known as sand-storage dams (Gur and Spuhler n.d.): A sand dam is a small dam built above ground and into the riverbed of a seasonal sand river, conditions that are found across the world's drylands. Sand dams are a type of decentralized storage of water that captures and stores water beneath sand (figure 9.4). Upstream of a sand dam, sand accumulates, resulting in additional groundwater storage capacity of riverbeds and riverbanks. During the wet season, this reservoir fills, preventing quick runoff of rainwater out of the catchment and prolonging water availability during dry seasons. Sometimes sand dams are fitted with a shallow well on the upstream side from which water will be drawn. Storing water in sand dams has advantages compared to conventional dams, including significantly reduced evaporation. Beyond 60 centimeters below the sand level, evaporation becomes negligible, and sand dams minimize water contamination through livestock and wildlife droppings and human use. They do not result in breeding of mosquitoes and do not take up valuable land. The technique of sand storage dams is not new: storage of rainfall and runoff, including subsurface storage, for beneficial use has been applied since 9,000 BCE.

Small water retention structure: Small water retention structures include small to very small impoundments with an impounded area <0.1 km² and a volume <0.2 hm³ (Lehner et al. 2011). Small dams, ponds, and tanks can be found all around the world where they are known under multiple names: tanks or johads in South Asia (Sri Lanka, India), açudes in Brazil, petits barrages, small reservoirs or micro-dams in Sub-Saharan Africa, lacs collinaires in North Africa, pequeñas presas in Mexico and South America, cisterns in Europe, and haffirs in Africa. These systems, despite their small global areal extent (3.8 percent of the global reservoir surface area) represent one of the most common features in freshwater landscapes (99.5 percent of the total number of reservoirs worldwide) (Downing et al. 2006; Lehner et al. 2011).

Snowpack: Snowpack is *"a seasonal accumulation of slow-melting packed snow."*[9] Snowpack has the largest geographic extent of the cryosphere components and

FIGURE 9.4 Sand Dam



Source: Based on Excellent n.d.
Note: Left: Cross-section of a sand dam. Right: Sand accumulates until the dam is completely full of sand up to the spillway. Water is stored within the sand, protected, and filtered, making up to 40 percent of the total volume (Gur and Spuhler n.d.).

covers nearly 50 million km² of the Northern Hemisphere in winter, affecting heavily populated mid-latitude regions as well as higher latitudes.[10] Snowpack can be part of glaciers, but not all snowpack is located on glaciers (Seibert et al. 2015).

Soil: Soil is defined as "*the biologically active, porous medium that has developed in the uppermost layer of Earth's crust.*"[11] Soils can process and hold a considerable amount of water. Stored water in soil is a dynamic property that changes spatially in response to climate, topography, and soil properties, and temporally as a result of differences between utilization and redistribution via subsurface flow (Western, Grayson, and Green 1999; O'Geen 2013). Water storage and redistribution are also a function of soil pore space and pore-size distribution (O'Geen 2013). *Soil moisture* refers to water stored in the unsaturated zone of the soil (Girotto and Rodell 2019). It influences the portion of rainfall going into runoff and infiltration, evapotranspiration and the magnitude and occurrence of flood water extremes, because when the soil is saturated, it cannot infiltrate any more water (Girotto and Rodell 2019). In parts of the tropics and in the midlatitudes, soil moisture variations are generally the largest driver of seasonal changes in water storage (Girotto and Rodell 2019). Much of this retained water can be used by plants and other organisms, thus contributing to land productivity and soil health (WCCag n.d.).

Subsurface dam: A subsurface dam obstructs the groundwater flow of an aquifer and stores water below ground level using geological strata (Gur and Spuhler n.d.). It is composed of a cut-off wall by which the groundwater flow is dammed (or intrusion of the seawater is prevented), and facilities like wells, intake shaft, and pumps draw up the stored groundwater (VSF 2006).

Urban sponge/sponge city: A sponge city refers to sustainable urban development including flood control, water conservation, water quality improvement, and natural ecosystem protection. It envisions a city with a water system that operates like a sponge to absorb, store, infiltrate, and purify rainwater and releases it for reuse when needed (Rui et al. 2018).

Watershed: A watershed is "*a land area that channels rainfall and snowmelt to creeks, streams, and rivers, and eventually to outflow points such as reservoirs, bays, and the ocean*" (NOAA n.d.). Watersheds provide water supply by concentrating precipitation inputs in space and distributing them over time, influencing both evapotranspiration and deep recharge (Guswa, Hamel, and Dennedy-Frank 2017). The flow-regulating benefits of natural watersheds are necessary to ensure reliable water supplies between periods of rain (Guswa, Hamel, and Dennedy-Frank 2017). However, this flow-regulating capacity may not be enough to ensure adequate water supply, so watershed management practices may be used to complement with additional water storage solutions, including landscape management practices. The storage capacity of a catchment can be increased, for example, with the construction of ponds or the restoration of wetlands, which in turn increase recharge to surficial aquifers to support sustainable pumping. Watershed or landscape water storage will be best realized with coordinated watershed-level plans, rather than a patchwork of individual efforts.

Wetland: Wetlands are defined as "*areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters*" (Ramsar 2007). Wetlands can include swamps, marshes, bogs, and the like. A wetland can collect and retain inflowing surface water (floodwater, snowmelt), direct precipitation, and discharging groundwater as standing water above the soil surface, pore water in the saturated zone, or soil moisture in the unsaturated zone. The characteristics and processes that influence the capacity of a wetland to store water over an extended period are related natural factors, such as climate, geomorphic characteristics, soils, and vegetation (Gilbert et al. 2006). They function as natural sponges that trap and slowly release water, providing several vital services such as flood protection, carbon sequestration, groundwater replenishment, pollution prevention and abatement, and biodiversity services.

ENDNOTES

1. Jasechko et al. (2017) define all groundwater that pre-dates the beginning of the Holocene (approximately 12,000 years BP) as fossil. UNESCO defines fossil groundwater as *"water that infiltrated usually millennia ago and often under climatic conditions different from the present, and that has been stored underground since that time."* (UNESCO 2006). Gleeson et al. (2015) further subdivide the non-fossil groundwater (younger

than 12,000 BP) into modern groundwater (younger than 50 years) and young groundwater (between fossil and modern) (Bierkens and Wada 2019).

[2] It can be referred to as “flood retention basin,” “in-stream flood control dam,” and "flood mitigation dam."

[3] https://web.archive.org/web/20160304070353/http://www.tmcd.org/flood/works.asp.

[4] https://en.wikipedia.org/wiki/Flood_control_channel.

[5] The rest is stored in the two continental ice sheets of Antarctica and Greenland.

[6] Floodgates, also called stop gates, are adjustable gates used to control water flow in flood barriers, reservoirs, rivers, streams, or levee systems. Unlike lock and weir gates, floodgates prevent the intrusion of flood or storm surge waters into the hinterland, instead of controlling water levels on inland waterways, and that floodgates are normally in stand-by condition and operate sporadically rather than being in permanent operation. (Daniel and Paulus 2019).

[7] A causeway is a raised path, railway, or road across an expanse of low ground, wetlands, or water. It is different from a bridge in that it has little or no opening underneath. Instead, it consists of a crest with embankments on either side. It is typically made of compacted earth, sand, and rocks. They can involve a combination of causeway and bridge segments (Serralheiro-O’Neill 2020).

[8] https://www.britannica.com/dictionary/river.

[9] https://www.merriam-webster.com/dictionary/snowpack.

[10] https://globalcryospherewatch.org/about/about_snow.html.

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