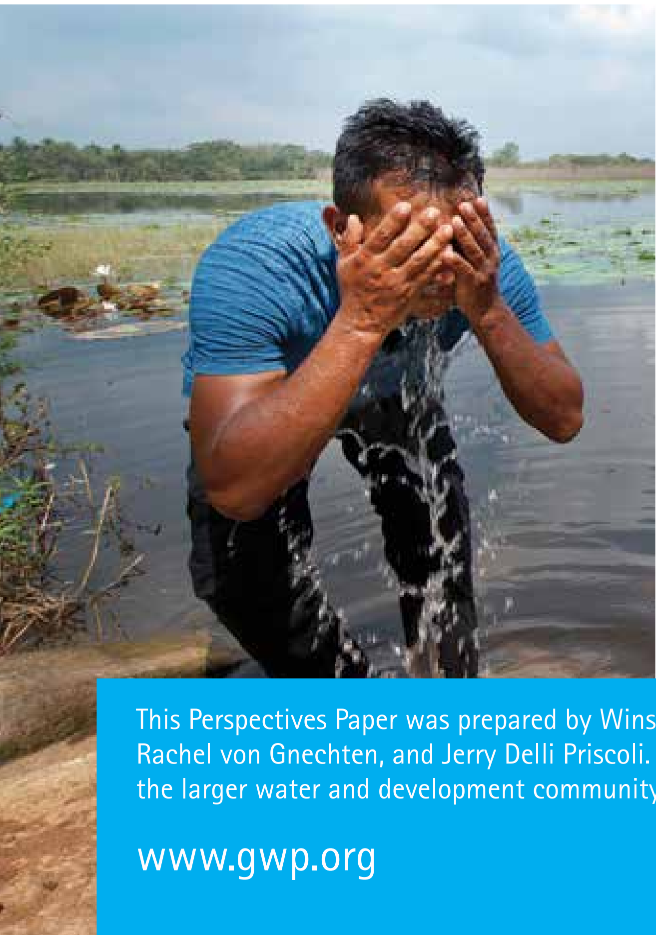
PERSPECTIVES PAPER

Storing water: A new integrated approach for resilient development



This Perspectives Paper was prepared by Winston Yu, William Rex, Matthew McCartney, Stefan Uhlenbrook, Rachel von Gnechten, and Jerry Delli Priscoli. It is intended to galvanise discussion within the GWP Network and the larger water and development community on the role of storage in managing water and building resilience.

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About GWP

The Global Water Partnership (GWP) vision is for a water secure world.

Our mission is to advance governance and management of water resources for sustainable and equitable development.

GWP is an international network that was created in 1996 to foster the application of integrated water resources management: the coordinated development and management of water, land, and related resources in order to maximise economic and social welfare without compromising the sustainability of ecosystems and the environment.

The Network is open to all organisations which recognise the principles of integrated water resources management endorsed by the Network. It includes states, government institutions (national, regional, and local), intergovernmental organisations, international and national non-governmental organisations, academic and research institutions, private sector companies, and service providers in the public sector.

The Network has 13 Regional Water Partnerships, 60 Country Water Partnerships, and more than 3,000 Partners located in 183 countries.

About IWMI

The International Water Management Institute (IWMI) is an international, research-for-development organization that works with governments, civil society and the private sector to solve water problems in developing countries and scale up solutions. Through partnership, IWMI combines research on the sustainable use of water and land resources, knowledge services and products with capacity strengthening, dialogue and policy analysis to support implementation of water management solutions for agriculture, ecosystems, climate change and inclusive economic growth. Headquartered in Colombo, Sri Lanka, IWMI is a CGIAR Research Center and leads the CGIAR Research Program on Water, Land and Ecosystems (WLE).

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Abstract

This paper outlines a new and integrated water storage agenda for resilient development in a world increasingly characterised by water stress and climate uncertainty and variability.

Storing water has long been a cornerstone of socio-economic development, particularly for societies exposed to large climatic variability. Nature has always supplied the bulk of water storage on earth, but built storage has increased significantly, particularly over the twentieth century. Today, numerous countries suffer from water storage gaps and increasingly variable precipitation, threatening sustainable development and even societal stability. There is a growing need to develop more storage types and manage existing storage better. At the same time, the policy, engineering, and scientific communities may not fully recognise the extent of these storage gaps and how best to manage them. There are large and uncertain costs and benefits of different types of storage, and developing storage can be risky and controversial. Although there is consensus that built and natural storage are fundamentally complementary, there is still no pragmatic agenda to guide future integrated water storage development.

This paper argues that water storage should be recognised as a service rather than only a facility. More than volumes of water stored behind a dam or in a watershed, what ultimately matters is the ability to provide different services at a particular time and place with a given level of assurance. Integrated storage systems should be developed and managed to deliver a targeted service standard. This will reduce the costs of new storage development and make the benefits more sustainable.

As this paper demonstrates, there are numerous data gaps pertaining to water storage, as well as a need for greater clarity on some key concepts. This paper does not introduce new data or research but rather provides a review of some of the current knowledge and issues around water storage, and outlines a new, integrated and constructive water storage agenda for the decades to come.

Highlights

- **There is a need for a new agenda on storage to support resilient development.**
- **Growing storage gaps will limit socio-economic development.**
- **Storage of all types are available and need to be better integrated, taking a service perspective.**

Foreword

The Intergovernmental Panel on Climate Change (IPCC) defines resilience as "the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner" (IPCC, 2012).

Throughout history, water resources management and water storage have provided critical tools for building resilience and laying the foundations for sustainable development. Stored water can be used for many purposes such as a wide range of productive services as well as for managing floods, droughts, storm surges, and other catastrophic events. Integrating various storage uses increases a society's ability to manage water under climate change risks and assists people and social systems to adapt to such events. Investments in water storage have proven vital to building socio-economic growth and social stability.

Today, two decades after the World Commission on Dams Report, our understanding of storage tools has expanded. While dams remain important, they include new varieties of human-made structures along with new methods of integrating natural storage. Given the global attention to building resilience, the importance of storage to resilience, the expanded understanding of different storage types, and the enhanced understanding of how to integrate water storage uses through integrated water resource management (IWRM), GWP and IWMI decided to collaborate on identifying a new agenda on water storage.

The GWP strategy (Mobilising for a Water Secure World) and the IWMI strategy (Innovative Water Solutions for Sustainable Development) both recognise the importance of water in adapting and building resilience to climate change. Urgent action on integrated storage will be essential to achieving these aims. This Perspectives Paper examines options and challenges for the water resources and climate change communities to re-look at the opportunities water storage offers.

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Introduction

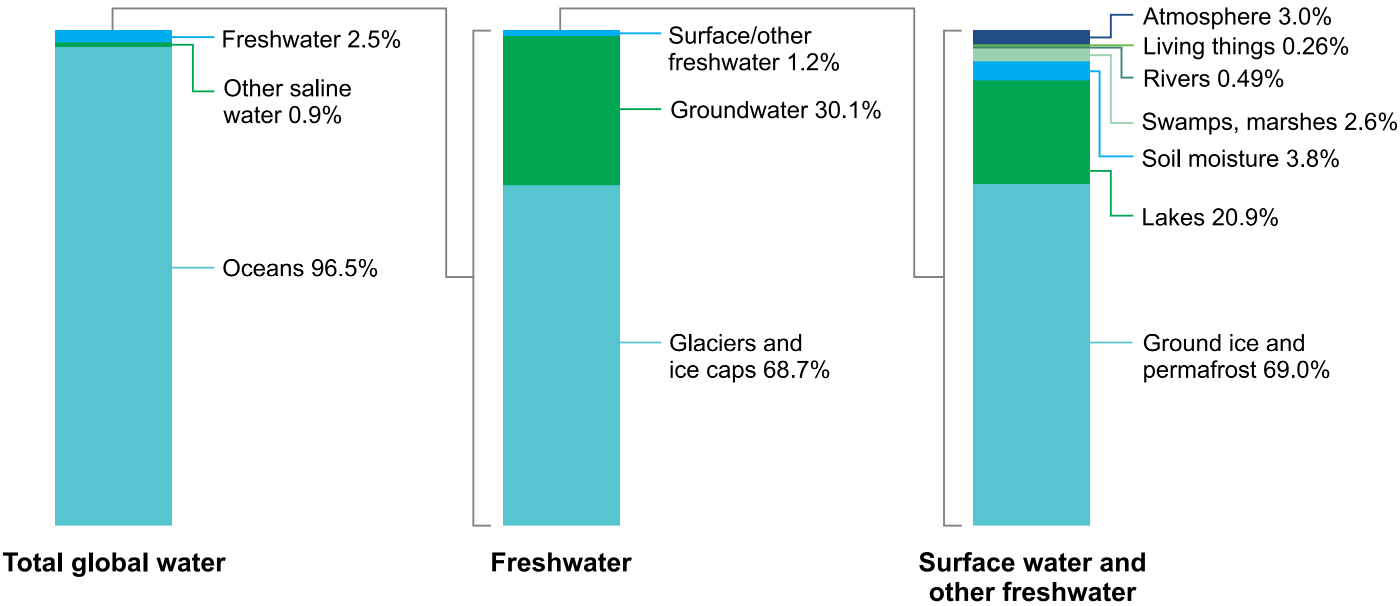
Water storage is essential to societies, economies, and ecosystems. Throughout the world, precipitation is naturally variable; periods with too much water are followed by periods with too little. The inability to manage short-term, seasonal, and interannual variability is a major impediment to livelihoods and a key constraint to socio-economic development in many places. Water storage provides a buffer for managing uncertainty and variability and adds adaptive capacity, thereby enabling modern cities to access water on demand, farmers to grow crops in dry seasons, animals to survive between rains, rivers to flow all year round, hydroelectricity to be generated, and many other important benefits and services.

Water is stored in natural and built systems above and below the ground. Most water on earth (97 percent) is stored in the oceans, but vast amounts of water are also stored in natural systems: glaciers, aquifers, wetlands, lakes, rivers, and in soils (Fig. 1). Water stored in human-built systems, such as dams, retention ponds, and tanks, remains, by comparison, relatively small but is nevertheless vital for many people's livelihoods and economic growth. Natural and built systems interact in both planned and unplanned ways.

Water storage is under growing pressure in many places around the world. Human demand for water continues to grow in many places as populations increase, diets change, and economies grow. Unless water resources and demand are evenly distributed across the year, this often translates into increased need for storage. This need is also made more urgent by climate change which is increasing the variability of rainfall, evaporation, and groundwater recharge, and modifying river flows in many places around the world. At the same time, both natural and human water stores are declining as glaciers melt, wetlands and other ecosystems degrade, and reservoirs fill with sediment. As this paper explores, while data are poor, there is likely a growing storage gap that countries will need to fill for both development and climate adaptation reasons.

Water storage is an important tool for resilience. The Intergovernmental Panel on Climate Change (IPCC) defines resilience as "the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner" (IPCC, 2012). Thus, water storage helps water managers deal with change, maintain services, or quickly recover after shocks (e.g. floods). This resilience is especially critical in the context of

Figure 1. Distribution of water stores



Source: US Geological Survey, Water Science School: https://www.usgs.gov/media/images/distribution-water-and-above-earth increased future variability and uncertainty in water availability. Combined with changing societal priorities and patterns of water demand, this adds up to considerable increased uncertainty and extensive debate about the best ways to manage future water resources. This paper argues that using a range of different water storage options in an integrated system enhances resilience. This type of system only fails when there are concurrent shortfalls in more than one storage type (McCartney et al., 2013a). Planning for and managing storage as an integrated 'system' rather than as disparate single facilities is a key step towards building resilience.

We need to shift our thinking around water storage. There have been numerous calls for better integration of natural and built infrastructure, (for example, Vörösmarty et al, 2018) conjunctive management of surface and groundwater, and consideration of a broader range of water storage options. However, there is far less thinking about what an integrated water storage approach for delivering services would look like in practice. Each type of storage has its own characteristics in terms of technical feasibility, socio-economic sustainability, impact on health of the environment, and institutional and stakeholder requirements. Each needs to be considered carefully within its biophysical, cultural, human, and political context. This paper reviews the evidence on different water storage types and considers what a new, twenty-first century integrated storage agenda might look like, to help future water managers turn good intentions into practice.

Roles and types of water storage

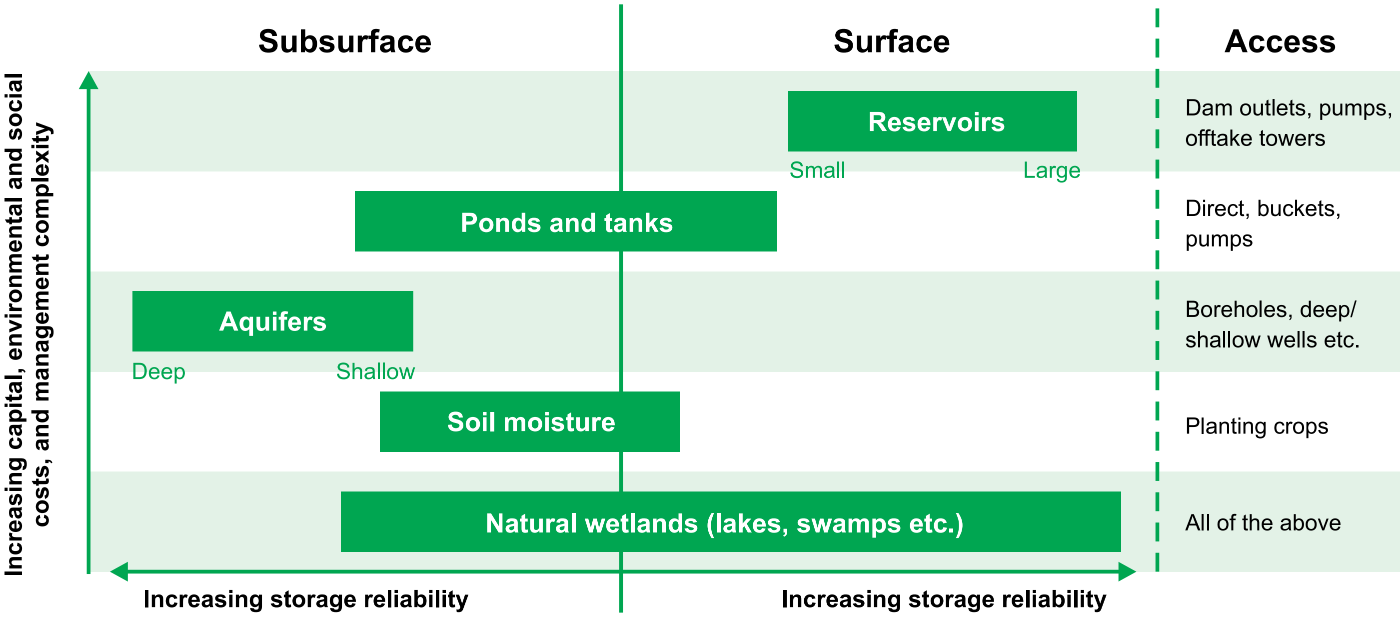
Water storage shifts resource availability across time. Storing water to balance inter-temporal problems is fundamental to meeting the variable and uncertain demands and needs of a society. Storage is essential to cope with temporal variability of water resources (Gaupp et al., 2015) and periodic shocks (e.g. floods and droughts). Any service that relies on a certain quantity and quality of water that is not always available in the right place at the right time must make use of storage. For example, storage makes it possible to provide many services (to different assurance levels), from the delivery of 24/7 drinking water to the application of irrigation water during critical growing stages of various crops, and meeting a variety of also time-dependent societal needs (e.g. navigation, recreation). Natural storage also regulates critical environmental processes and services (e.g. fish migration, sediment, water quality). Storage can serve as a rechargeable battery for an energy system (i.e. pump storage), allowing operators to more effectively manage different sources of electricity generation against different energy demands in time. Storage can also act as insurance against a future time of scarcity or as a buffer for times of excess. In summary, storage is an essential contributor to water security.[1]

There are many types of storage with different characteristics. Societies relied on different forms of natural storage long before they knew how to construct alternatives. Human settlements were typically located near rivers, lakes, wetlands, and reliable natural springs fed by aquifers to provide people with a year-round water supply. As populations grew, the need to modify the landscape to create additional storage also grew. Human-made water storage varies in size from the smallest household water tanks to huge artificial lakes (reservoirs) created behind dams. Each form of storage has different characteristics in terms of volume, feasibility, adaptability, controllability, reliability, vulnerability, sphere of control, cost, and sustainability (Fig. 2 and Table 1). Moreover, there is a continuum between fully green (i.e. natural) and grey (i.e. built) storage as well as important interdependencies (Muller et al., 2015; Palmer et al., 2015).

Natural bodies of water provide storage. Both lakes and wetlands are important natural stores of water that are widely utilised for domestic water supply and agriculture around the world. Natural seasonal and interannual variability results in significant changes in these stores. In addition, human interventions can change their availability. Withdrawals, primarily for irrigation, have led to significantly reduced volumes in some lakes (e.g. the Caspian Sea and the Aral Sea). Wetlands have also been degraded by direct drainage,

[1] Water security has been defined as "the reliable availability of an acceptable quantity and quality of water for health, livelihoods and production, coupled with an acceptable level of water-related risks" (Grey and Sadoff, 2007).

Figure 2. Water storage continuum



Source: McCartney and Smakhtin (2010).

Table 1. Characteristics of storage

Attribute	Definition
Volume	The quantity of water stored
Feasibility	Practicality of implementing the proposed storage
Adaptability	The ability to adjust or modify storage to new conditions, uses, or purposes
Controllability	The degree to which the volume of water stored may be operated for a specific intended purpose
Reliability	The frequency of failure of the storage to deliver water to satisfy all demands (including the environment)
Vulnerability	The extent of failure of the storage to deliver water to satisfy all demands (usually determined in terms of magnitude of the failure and the time over which the failure lasts)
Sphere of control	The spatial and temporal extent of impacts from the services provided from storage that can be directly controlled through storage
Cost	Defined in full economic terms to include not only capital and operation and maintenance costs, but also opportunity costs and economic, social, and environmental externalities
Sustainability (environmental)	The ability to maintain an ecological balance and ensure ecosystem processes and functions in the future

peat harvesting, infilling or burning (e.g. peatlands), and from disrupted hydrological regimes (e.g. from upstream dams). These natural features, in some circumstances, can also play an important role in flood protection systems. For example, the Yolo Bypass (operated by the US Army Corps of Engineers and the California Department of Water Resources), a 240 km^2 wetland area along a natural depression near the city of Sacramento, California, is an important feature of California's flood management system (capable of conveying 80 percent of the Sacramento River during high-water events). Use of this wetland also generates environmental, fishery, and agriculture co-benefits (Sommer et al., 2011).

Groundwater represents a major store of water. The global groundwater resource is estimated at around 23,400,000 billion cubic metres (BCM) (Oki and Kanae, 2006). Earlier studies suggest that about 54 percent is saline and about 46 percent fresh (Gleick, 1996). Thus, excluding the ice caps and glaciers, total fresh groundwater reserves are about 100 times larger than fresh surface water stores. Though much of this water may not be accessible for society's purposes (either economically or technically), it represents an immense water store that is generally less susceptible to anthropogenic pollution than surface water. Traditionally, the accessibility of groundwater through dug wells, at springheads, and in seepage areas controlled the extent of human settlements beyond major river valleys. Deep drilling and pumping machinery introduced in the 1970s have enabled the expansion of areas using groundwater. Today, over large areas of rural land, it is only the presence of successful boreholes that allows human populations to survive. Globally, more than 2 billion people depend on groundwater for domestic supplies (Ajami, 2020). The extent to which groundwater represents a sustainable store of water differs greatly by place. The large area estimates from NASA's Gravity Recovery and Climate Experiment (GRACE) mission suggest that groundwater is being extracted at unsustainable rates in parts of South Asia, the Middle East, and North America (Famiglietti et al., 2011; Rodell et al., 2009; Voss et al., 2013). On the other hand, a large groundwater resource in Africa remains relatively untapped (MacDonald and Calow, 2009; Altchenko and Villholth, 2015).

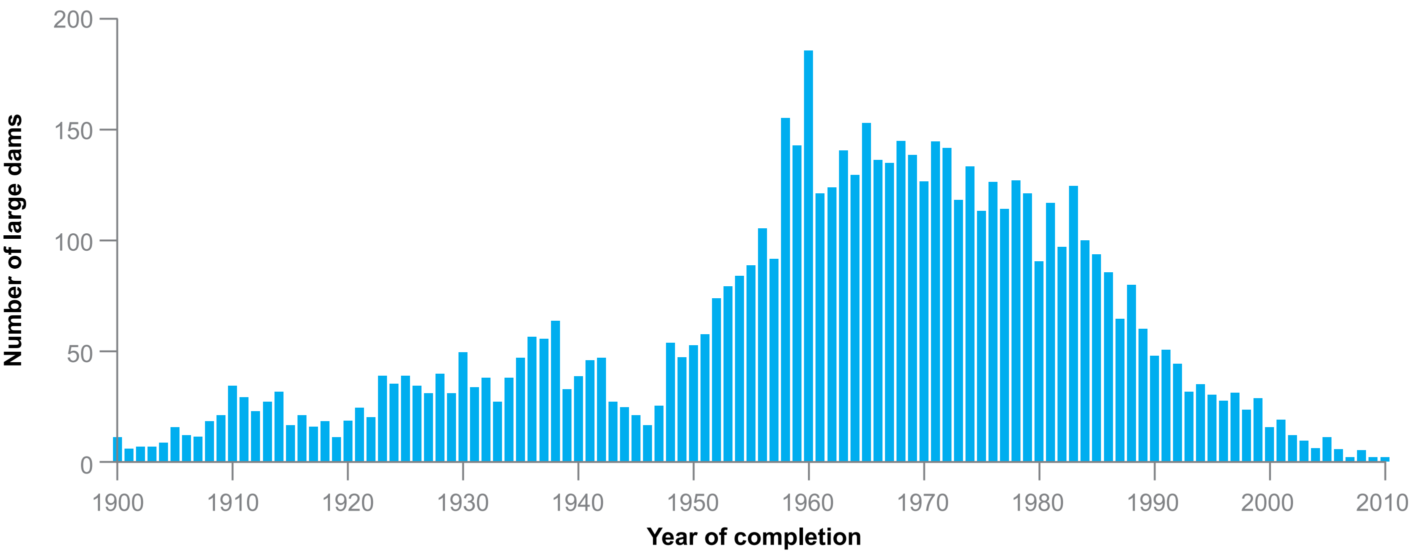
The storage opportunities provided by aquifers have long been recognised. (see e.g. gripp.iwmi.org). Aquifer storage and recovery, which is the intentional recharging of an aquifer with an intent to use the water later, has been done for centuries (Dillon et al., 2018). This may also have positive impacts on water quality. Stefan and Ansems (2018) developed a global inventory of managed aquifer recharge experiences consisting of about 1,200 case studies across 62 countries. Sprenger et al. (2017) demonstrated that, for more than a century, managed aquifer recharge has been used to develop water supplies across Europe. Similarly, much has been written about the conjunctive management of surface and groundwater (e.g. Alam et al., 2020). In the Middle East and North Africa region, aquifer storage in combination with desalination and greater reuse of reclaimed water is seen as a solution to water scarcity challenges (Ghaffour et al., 2012). As described in Amarasinghe et al. (2016), the Ganges Water Machine, a concept proposed 40 years ago in India, aims to reduce flood risks by generating subsurface storage through accelerating the use of groundwater before the onset of the monsoon season, and subsequent recharging of this storage with monsoon flood waters. Thus, greater active recharge at suitable locations will help both the long-term sustainability of the resource and the conjunctive management of the storage available.

Water can be stored in soils in the landscape. Soils play an important role in the rainfall–runoff response of a catchment. Globally, the total volumes of water stored within soils are small compared with other natural terrestrial stores. Estimates are about 16,500 BCM (Shiklomanov, 1993). The capacity of soils to regulate the terrestrial freshwater supply, including water quality, is a fundamental ecosystem service. Land use changes, for example, deforestation, urbanisation, and soil and water conservation measures such as bunds and erosion prevention, can alter the water stored in soils. In particular, because of its significant share of total land use, agricultural management practices (e.g. tillage practices, deep ploughing, irrigation and drainage, buffer strips, and buffering zones) can alter hydrological properties and lead to changes in soil water storage (OECD, 2016).

Apart from groundwater, snowpacks and glaciers are the largest natural water storage element. Seasonal meltwater from snow and ice contribute significantly to river flows that sustain the livelihoods of billions of people (Mark et al., 2015; Viviroli et al., 2020). More than one-sixth of the Earth's population relies on glaciers and seasonal snowpacks for their water supply (Barnett et al., 2005). For some of the world's largest basins (e.g. Ayeyarwady, Mekong, Ganges, Brahmaputra), the contribution of glacial melt to total river flow is small. However, this may nonetheless act as an important hydrologic buffer, particularly during the dry season and in dry years for many smaller rivers (e.g. headwater tributaries). Climate change impacts on snowpacks and glaciers are reducing this natural storage (Immerzeel et al., 2010). It is well documented that glaciers are retreating (Thompson et al., 2003; WCRP, 2018). Consequently, this may severely impact future water availability and its timing for communities worldwide. For example, Stewart et al. (2004) report an observed earlier shift in the timing of springtime snowmelt (10–30 days) for many western North American rivers (responsible for 50–80 percent of the total flow). New profiles of variability will emerge as this natural storage decreases (Mark et al., 2015).

Human-made storage has been developed to play a key role in water management. As human needs have extended beyond that which nature has been able to provide, humans have constructed a broad variety of water retention structures at a variety of scales. Since 1950, humans have constructed more than 57,000 large dams globally (ICOLD, see https://www.icold-cigb.org/). Human-made reservoirs now cover approximately 0.26 Mkm^2 (i.e. 0.2 percent of the global land area; Messager et al., 2016) and cumulatively store 9,400 BCM ± 3,100 BCM of water (Frederikke et al., 2020). Dams have been constructed to increase the reliability of bulk water supply to urban areas, irrigation schemes, and industry, to generate hydropower, manage floodwaters, and to enable navigation of rivers – all often in combination. They have also sometimes provided recreational facilities and opportunities to support fisheries. The world saw a major boom in large multipurpose dam building during the 1960s and 1970s (Fig. 3), but new construction has slowed considerably since that time, likely reflecting a combination of reduced opportunities (the best sites were occupied early) and a changing understanding of their costs and benefits. Societies have become sensitised to the large social and environmental costs

Figure 3. Global large dam construction (1900–2010)



Source: Global Reservoir and Dam (GRanD) Database.

[2] The International Commission on Large Dams (ICOLD) defines a large dam as any dam above 15 metres in height (measured from the lowest point of foundation to top of dam) or any dam between 10 and 15 metres in height which meets at least one of the following conditions: a) the crest length is not less than 500 metres; b) the capacity of the reservoir formed by the dam is not less than 1 million cubic metres; c) the maximum flood discharge dealt with by the dam is not less than 2,000 cubic metres per second; d) the dam had especially difficult foundation problems; and e) the dam is of unusual design.

of dams and their sometimes uncertain financial returns, as well as their vulnerability to sedimentation. Many large dams have also reached or exceeded critical ages (Perera et al., 2021). These concerns over large dams have pushed planners to consider alternatives.

Numerous small storage facilities have also been constructed. The interest in developing small dams (Venot and Krishnan, 2011) reflects in part the challenges of minimising environmental and social impacts and financing large water infrastructure. While the data on smaller dams are less comprehensive, large numbers of these structures exist (possibly of the order of millions; Table 2), collectively storing large amounts of water. Lehner et al. (2011) estimate that small reservoirs (those with a surface area between 0.01 ha and 0.1 ha) have a cumulative storage capacity of 1,873 BCM. Most often small dams are built to support irrigation, but they may also contribute to local water supply, livestock watering, and other community economic activities such as fisheries. There is also a wide range of different 'small' dams. Across different regions and countries, these may have different names including, inter alia, small reservoirs, farm and fish ponds, silt retention dams, micro-dams, valley dams, tanks and anicuts (South Asia), petits barrages and check dams (West Africa), açudes (Brazil), charco dams (East Africa), microdams (Ethiopia), sand dams (Limpopo), hillside dams (Kenya), berkads (Somalia), and hafirs (Sudan). There are likely to be other terms used as well (especially in local languages).

Urban environments are increasingly being designed with water storage in mind. Bioretention basins in urban environments are used to reduce and treat inflows into the stormwater system (Trowsdale and Simcock, 2011). For example, Bonneau et al. (2020) show that in Melbourne, Australia, the use of bioretention basins helped to reduce the delivery of polluted water to nearby streams by 55–65 percent while reducing peak flows. Other examples include the 'sponge city' concept in China in which wetlands and green spaces are used to retain and store water (Chan et al., 2018). At the same time, greening urban areas has several other co-benefits, such as, enhanced groundwater recharge, erosion control,

Table 2. Estimated numbers of small dams for selected countries

Country	Number (source)
Sub-Saharan Africa	
Burkina Faso	> 1,700 (Andreini et al., 2009)
Ethiopia	> 110
Ghana	> 1,000
Côte D'Ivoire	> 600
Mali	~ 800 (FAO, 2008a)
Mauritania	~ 350
Mozambique	> 600 (World Bank, 2008)
Niger	~ 100 (FAO, 2008b)
Uganda	> 425 (Bashar et al., 2003)
Zambia	2,000–3,000 (NCG, 2010)
Zimbabwe	~ 10,000 (Sugunan, 1997)
North Africa and Middle East	
Algeria	> 1,000 (Morsli et al., 2007)
Morocco	> 120 (Laamrani et al., 2006)
Tunisia	> 610 (Boufaroua et al., 2003)
Syria	> 50 (Albergel et al., 2007)
Rest of the world	
Brazil (Nordeste)	> 70,000 (Molle and Cadier, 1992)
India	> 208,000 (Palanisami, 2008)
Mexico	~ 12,000 (Sugunan, 1997)
Thailand	~ several thousands (Sanguan, 2000)
Sri Lanka	> 15,000 (Sakthivadivel et al., 1997)

Source: Venot and Krishnan (2011; references in this table can be found in this publication).

micro-climatic benefits, recreational values, and improvements to water quality.

The effectiveness of built storage depends on natural storage and catchment characteristics and vice versa. Research has highlighted that the hydrologic and biophysical characteristics of the catchment upstream of built infrastructure has a direct impact on the performance of that infrastructure. Specific catchment characteristics such as vegetation, soil type, geology, slope, and catchment size influence the rainfall–runoff response and sediment yields (Chorley, 1969). Land use and land cover (i.e. land management practices) can also modify these natural processes. Investments in watershed management, afforestation and reforestation, riparian buffer strips, and terracing affect both runoff generation and soil erosion. In turn, these affect the reliability, vulnerability, and long-term sustainability of downstream dams (McCartney et al., 2019). For example, in the Tana River in Kenya, soil and conservation measures reduced soil loss, reduced suspended sediment, and increased dry-season river flow, benefiting both energy and water services downstream and farmers upstream (TNC, 2015).

All storage types are potentially vulnerable to the impacts of climate change. By modifying both water availability and water demand, climate change will affect the performance, cost, and impacts of different types of water storage. Some storage options will become impracticable while the viability of others may be enhanced over time. For example, climate change may have significant direct impacts on the water stored in soils. In arid regions, the proportional change in soil moisture can be much greater than the proportional change in rainfall (Chiew et al., 1995; de Wit and Stankiewicz, 2006). Groundwater storage in coastal aquifers may be at risk from saltwater intrusion due to sea-level rise. Changes in river flows may also mean that reservoir yields, and hence the reliability of water supplies, decline. Furthermore, both natural and built storage may be at increased risk of both eutrophication and flood damage under climate change. Wetlands also face a range of climate change-related threats arising from changes in hydrological fluxes and temperatures, as well as increased anthropogenic pressures (McCartney et al., 2013b). Finally, climate change is likely to affect the externalities associated with different storage types. For example, malaria transmission in the vicinity of some ponds, tanks, and reservoirs may increase as the result of modified rainfall patterns and higher temperatures (Boelee et al., 2013; Kibret et al., 2012). Table 3 summarises some of the potential consequences of climate change for different water storage types and indicates some possible socio-economic implications.

In summary, all types of storage should be considered as part of an integrated co-dependent storage system. The traditional way of thinking about storage is to treat natural storage as part of the 'baseline' and to focus on what additional built infrastructure is needed. This approach is inadequate for several reasons. First, natural storage is being depleted. Second, built infrastructure can have many externalities. Third, there is significant interaction and co-dependency between natural and built storage (Hurford et al., 2020) that needs to be considered in planning and in operations. There may even be important co-benefits (e.g. emissions reductions) to consider for example, degrading watersheds may also degrade dams via increased sedimentation, or storing water in dams may reduce downstream aquifer recharge. The challenge, therefore, is not only to think more broadly about the different types of storage available, but also to consider storage facilities as part of a larger integrated system for improved resilience in water management and service delivery. Many have called for better integration of green and grey approaches (Browder et al., 2019; UN, 2018), although it is difficult to identify the best blend of solutions depending on local boundary conditions. Nonetheless, within any basin or landscape, considering the different characteristics that each type of storage provides (i.e. volume, feasibility, adaptability, controllability, reliability, sphere of control, cost, vulnerability, and sustainability) means that and managers have more possible approaches available to deal with the multidimensional water challenge.

Table 3. Climate change risks for different storage types and possible socio-economic implications

Storage type	Risks associated with climate change	Socio-economic implications
Reservoirs	■ Reduced inflow, resulting in longer periods between filling ■ Higher evaporation, increasing the rate of reservoir depletion ■ Infrastructure damage due to higher flood peaks ■ Improved habitat for disease vectors (e.g. mosquitoes) ■ Increased risk of eutrophication and salinisation ■ Increased siltation	■ Increased failure to meet design specifications (irrigation and hydropower generation, etc.) ■ Increased costs due to the need to redesign infrastructure (e.g. spillways) ■ Increased risk of waterborne diseases (e.g. malaria)
Ponds/tanks	■ Reduced inflow, resulting in longer periods between filling ■ Higher evaporation, increasing rates of depletion ■ Infrastructure damage due to higher flood peaks ■ Improved habitat for disease vectors (e.g. mosquitoes) ■ Increased risk of eutrophication and salinisation ■ Increased siltation	■ Increased failure to meet water requirements of the community and households ■ Increased labour requirements and costs to repair structures ■ Increased risk of waterborne diseases (e.g. malaria)
Aquifers	■ Reduced recharge, resulting from modified rainfall intensities ■ Reduced recharge, resulting from land-cover modification and increased soil moisture deficits ■ Saline intrusion in aquifers near the coast	■ Falling water levels, which make it increasingly costly to access groundwater ■ Reduced water quality, which makes groundwater unsuitable for use
Soil moisture	■ Reduced infiltration, resulting from modified rainfall intensities ■ Waterlogging, resulting from modified rainfall intensities and duration ■ Longer dry periods, resulting from altered temporal distribution of rainfall ■ Depleted soil moisture, arising from higher evaporative demand ■ Soil erosion, resulting from modified rainfall intensities and duration ■ Reduced soil quality (including water-holding capacity and nutrient status), resulting from modified rainfall and temperature	■ Decreased productivity – more frequent crop failures and reduction in yields
Natural wetlands	■ Reduced rainfall and runoff inputs, resulting in wetland desiccation ■ Higher flood peaks, resulting in wetland expansion and flooding of fields and homes ■ Improved habitat for disease vectors (e.g. mosquitoes)	■ Increased failure to provide water requirements of the community and households ■ Loss of water-dependent ecosystem services (including flow regulation and groundwater recharge) ■ Increased risk of waterborne disease (e.g. malaria)

Source: modified from McCartney et al. (2013a).

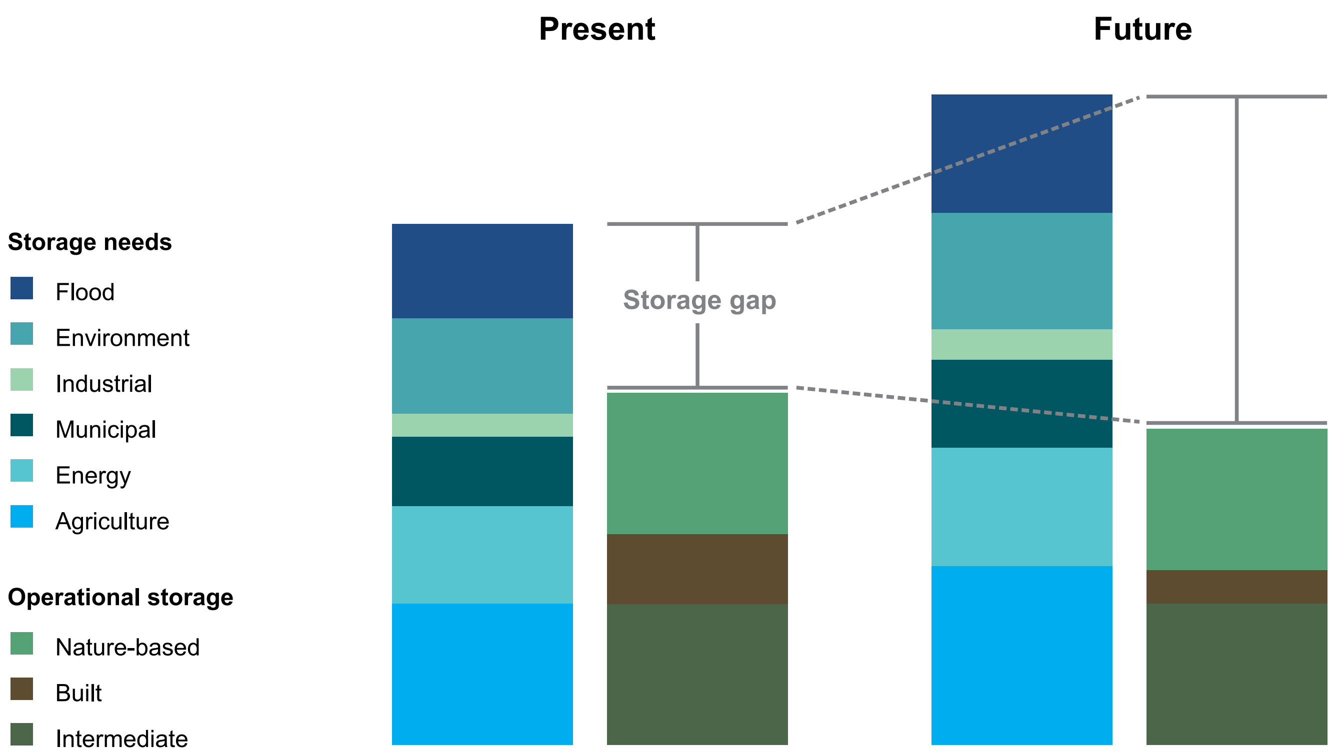
A growing water storage gap

A 'water storage gap' is defined as the difference between the amount of water storage needed and the amount of storage that exists for a given time and place. While the size of the 'gap' will differ according to the assumptions made to measure it, the basic concept is a useful way to discuss the amount of additional water storage – and the types of storage – that need to be developed (or re-operated) to support the delivery of services and enable more resilient societies, economies, and environments.

Many infrastructure gap analyses do not explicitly look at storage requirements. In recent years, there have been several reports identifying current infrastructure gaps (e.g. Oxford Economics and Global Infrastructure Hub, 2017; Rozenberg and Fay, 2019). These typically focus on traditional infrastructure sectors, such as roads, water supply, irrigation, wastewater treatment, flood protection, and power plants. These gaps are typically calculated with respect to country-level policy objectives (e.g. achieving the Sustainable Development Goal (SDG) targets on water supply and sanitation, and acceptable flood risks) and public sector efficiency. Though storage needs may be indirectly accounted for (e.g. by multipurpose dams), storage itself (of all types) and the multiple services provided are often not explicitly considered.

Several key mega-trends suggest that the water storage gap in many places is growing, at least in relative terms. Though good comparable data are scarce, some big trends are relatively clear (Fig. 4): a) demand for water services is growing in many places due to population and demographic changes, and economic growth; b) growing uncertainty and variability in climate, particularly precipitation, means a growing need for storage; c) available storage is under pressure from sedimentation locally (for dams) and environmental degradation and climate change more broadly (for natural storage); and d) the socio-economic costs of floods and droughts – for which storage is a key mitigation measure – are growing. Thus, the demand for storage is increasing while the supply of storage is decreasing. The picture at the country or local levels will differ greatly; some countries may experience little pressure while others already have significant water storage gaps which will likely worsen over time.

Figure 4. A growing storage gap



The economic costs of this increasing storage gap are potentially significant. The economic benefits of providing water services are clear; for example, from the positive impacts of water supply and sanitation services on health and human productivity (WHO, 2012) to the contribution of irrigation services to reducing poverty and promoting rural growth (Hussain and Hanjra, 2004; IPTRID, 1999). Without storage, these services cannot be provided reliably (i.e. meeting these demands in space and time). At the same time, insufficient storage makes countries vulnerable to extreme events (e.g. floods and droughts). The economic losses from these events are well documented in the literature (Brown et al., 2013).

Global gross domestic product (GDP) losses from river floods total roughly US$96 billion per year, with the world's poorest countries the most vulnerable (Luo et al., 2015). More generally, the relationship between climate variability and economic performance has been demonstrated in several countries such as Tanzania and Ethiopia – Fig. 5 (modified from van Aalst et al., 2007). For example, in sub-Saharan Africa, economic growth varies across countries (measured in terms of GDP per capita), each faced with different degrees of intra-annual variability, and with different existing levels of storage, both built and natural (Fig. 6). Thus, for some countries, a lack of storage may result in greater economic burdens and be a drag on development.

Figure 5. Relationship between rainfall variability and growth in gross domestic product (GDP)

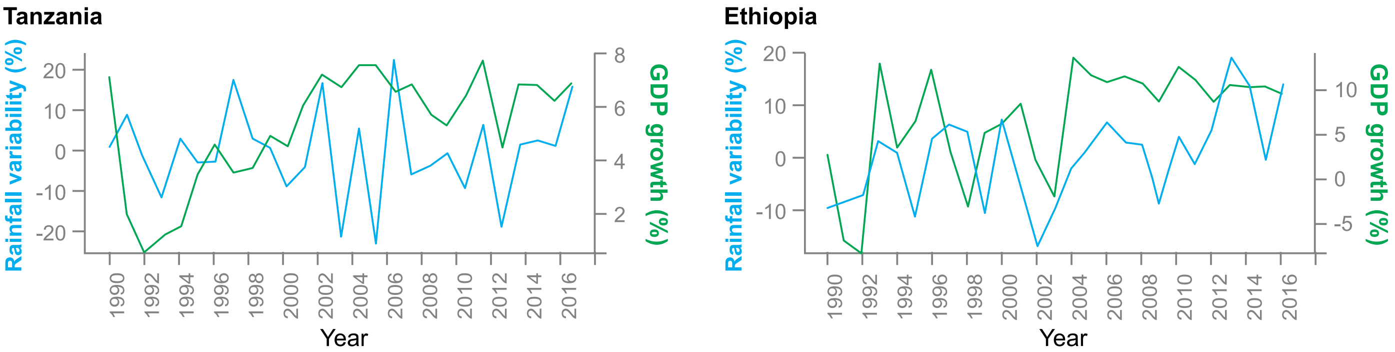
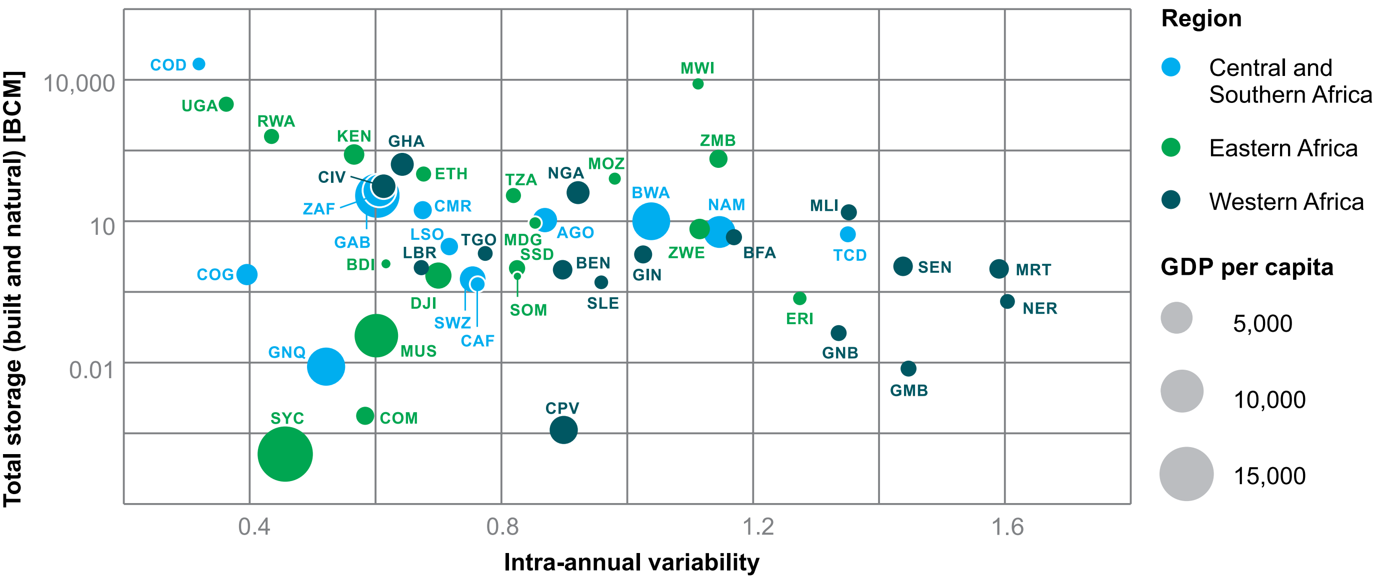


Figure 6. Total surface water storage in billion cubic metres (BCM) versus intra-annual rainfall variability for sub-Saharan Africa countries



Note: Total storage is defined as the sum of water stored in reservoirs and water stored in lakes in billion cubic metres (in log-scale); the size of the circle is the country's gross domestic product (GDP) per capita (US$). Source: World Bank Climate Change Knowledge Portal, World Development Indicators and Messager et al. (2016).

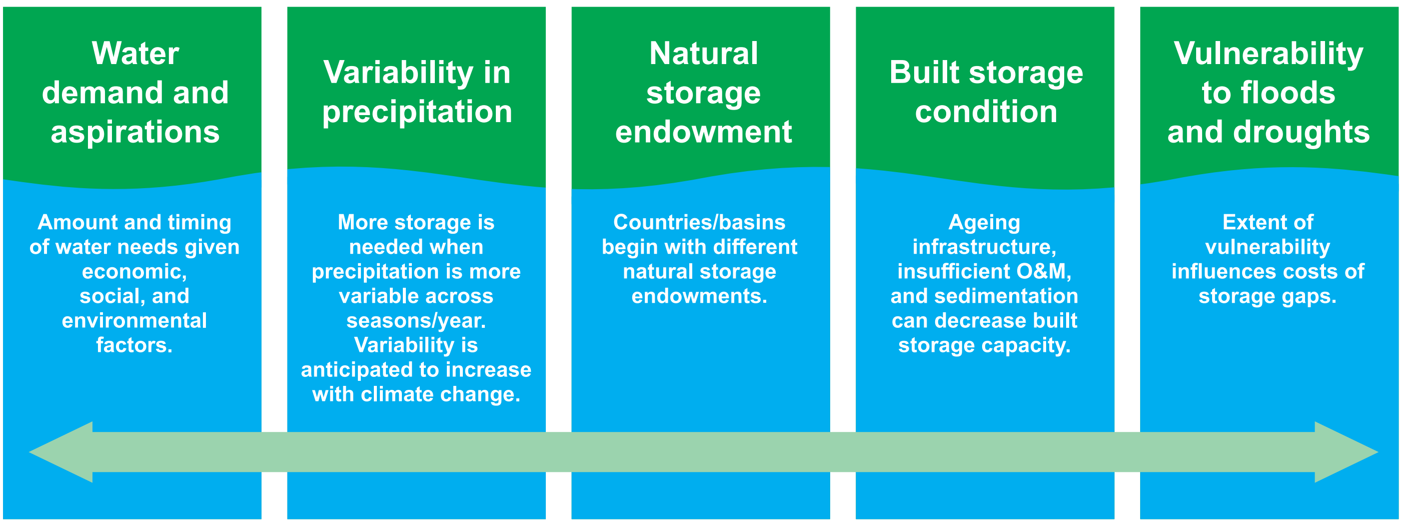
Storage demand

Is there a minimum amount of storage needed? How much storage is needed is dependent on a country's goals across various water-related subsectors (e.g. domestic food production, hydropower targets, environmental protection), the extent of variability in precipitation (both temporal and spatial at various scales), and a country's vulnerability to floods and droughts, as well as a country's natural storage endowment (Fig. 7). Brown and Lall (2006) calculate the storage that is needed for every country to transfer water from wet months to dry months to meet food needs on an annual basis. The authors note that the GDP of those countries lacking adequate storage is notably low. Similarly, countries may have hydropower generation targets that imply a quantity of storage needed. Storage needs are also dynamic, and minimum requirements may increase in the future with demographic and consumption shifts and because of increasing variability and uncertainty (due to, for instance, climate change or food system transformations). In thinking about how much storage is needed, 'storage volume per capita' benchmarks are often used to compare across countries. Though perhaps useful for regional comparisons, such a metric may be problematic for cross-country comparisons as different countries may have different needs that are independent of the population size (e.g. flood risks, hydro-climate variability).

Storage supply

Systematic data on built storage is limited; however, there are innovative remote sensing approaches to fill some of the data gaps. ICOLD maintains the largest of the global large dams datasets. This member-contributed registry includes 59,071 large dams. However, this dataset is not geo-referenced, does not include data on live storage, and does not provide information on the allocation of storage to different purposes or countries, where they are shared. Many researchers have used remote sensing techniques to catalogue and monitor built storage (e.g. Annor et al., 2009; Eilander et al., 2014; Ghansah et al., 2018; Lehner and Döll, 2004; Liebe et al., 2005; Mialhe et al., 2008; Sawunyama et al., 2006). Two larger databases are the Global Reservoir and Dam database (GRanD) by Lehner et al. (2011) and the Global Geo-referenced Database of Dams (GOODD) by Mulligan et al. (2020). Lehner et al. (2011) demonstrate with GRanD that 7,320 dams store 6,881 BCM. From this, they estimate that over 16 million reservoirs of all sizes with a combined storage of over 10,000 BCM may exist globally. This is consistent with other studies (e.g. Chao et al., 2008; Frederikse et al., 2020). Artificial intelligence approaches have also been developed to identify small dam infrastructure (Weil, 2018). It is important to recognise that with these remote sensing approaches, identifying the water surface area works

Figure 7. Drivers of water storage development needs



reasonably well (Pekel et al., 2016). However, translating this to estimates of actual storage volume is more difficult. Moreover, this research points to the greater challenge of identifying the locations of smaller distributed storage facilities. Many countries report limited knowledge on the locations and status of small storage units (of all types). Pisaniello et al. (2012) find in Vietnam, for example, which has thousands of small dams, that there is no national record of these dams nor the storage conditions associated with them (i.e. no systematic data on type, size, hazard ratings, technical conditions). This is problematic as the cumulative impacts, particularly from a dam safety perspective, may be far greater than for a single large dam. Finally, there are also other built stores beyond dams that are typically not inventoried (e.g. rainwater harvesting tanks).

An inventory of natural storage is needed. The distinction between natural and built surface water bodies (particularly from space) is not always easy to discern. Lehner and Döll (2004) developed the Global Lakes and Wetlands Database which captures approximately 2.7 million km^2 of lakes and reservoirs and 8–10 million km^2 of wetlands. More recently, Messager et al. (2016) developed HydroLAKES (see www.hydrosheds.org), a database of more than 1.4 million water bodies including freshwater and saline lakes, human-made reservoirs, and regulated natural lakes. Remote sensing techniques can also be used to identify other natural stores such as changes to groundwater and the extent of glaciers and snowpacks on the planet. The US National Snow and Ice Data Center maintains maps of global snow cover using satellite imagery (Hall et al., 2006) and an inventory of over 130,000 glaciers. Mapping of underground storage (soil water and groundwater) remains particularly challenging, as remote sensing techniques only work for the upper centimetres of the soil or allow only for spatially coarse resolution estimates of groundwater storage changes (e.g. Sun, 2013). Measuring or estimating the volume of natural storage and the services that depend on it is a key step towards being able to protect or develop this storage further. Though not all this natural storage is 'controllable' by the water manager, it still has important functions (e.g. hydrologic buffering) as part of an overall integrated storage system.

Available storage is dynamic. Every year, land temporarily stores then releases approximately 6,000 BCM of water through seasonal cycling (Reager et al., 2016). Natural and human perturbations to this cycling superimpose trends in storage over annual and decadal timescales. Other than the melting of ice, human modification of storage includes: a) the filling of reservoirs behind human-made dams, which is partly offset by sedimentation; b) groundwater depletion; c) drainage of endorheic lakes; d) drainage of wetlands, which is partly offset by the construction of human-made wetlands, such as paddy fields; e) deforestation; and f) changes in soil moisture, permafrost, and snow (Wada et al., 2017). Some of these modifications add to water stored, while others reduce water stored. Generally, the vast spatial scale of these changes in land and water storage are too difficult to observe with accuracy. Thus, despite recent advances in coupled (terrestrial–ocean–climate) modelling and satellite measurements (e.g. NASA's GRACE), there remains considerable uncertainty in the changes to many of these water stores.

Available storage is likely to be decreasing. Wisser et al. (2013) estimate that built net storage (installed capacity minus sedimentation losses) peaked in 2007. This reflects a slowdown in the construction of dams since the 1970s as well as an estimated loss of storage due to sedimentation (c.5 percent loss or 270 BCM over the study time period). Moreover, per capita storage has been steadily declining in many river basins since the 1980s. Maintaining this existing stock of built storage requires substantial maintenance efforts. Palmieri et al. (2003) estimate that just to replace the storage that is lost annually as a result of sedimentation would cost over US$13 billion per year. At the same time, as discussed earlier, some natural storage is also declining (e.g. snowpack and glaciers, forests, wetlands). For example, Zemp et al. (2006) demonstrate that the total glacier volume in the European Alps is now close to a third of the volume measured in 1850 (200 BCM) and is expected to continue to decline under warming conditions. A more recent global study estimates that mountain glaciers have lost 8,666 BCM between 1961 and 2016 (WCRP, 2018).

Changes to sea-level rise can be used as a partial proxy for changes in storage. Long-term average sea-level change is primarily influenced by changes to sea temperature and the amount of water stored in ice or over land. Disaggregating these influences is the subject of a growing literature (Table 4). From these studies, an estimate of the change in total water stored from different components of the landscape could be determined over the 50-year period 1970–2019. Excluding the storage from the Antarctic and Greenland ice sheets, the estimated net loss from all other stores (including mountain glaciers) is approximately 15,700 BCM. This points to an increasing storage gap at the global level. While the net storage loss appears small compared with the total storage (<1 percent) at the global level, the relative change in storage at country and local levels could still be significant and should not be overlooked. Moreover, large parts of groundwater storage (approx. 98 percent of the considered current terrestrial storage) are inaccessible (i.e. resources are too deep, too hard to extract or too far from the user) and may not interact with the broader hydrologic cycle at timescales (months to decades) relevant to water management. Finally, it is important to note that these changes in storage can be either human-induced or driven by climate change.

Table 4. Estimated terrestrial freshwater storage and change over the period 1970–2019

Water stores	Current storage (BCM)	Change in storage (BCM)	Change is human (H) or climate (C) driven	Source
Mountain glaciers	158,000	−8,666	C	Total storage: Farinotti et al. (2019). Rate of change: WCRP (2018)
Groundwater	10,396,000*	−7,041	H/C	Total storage: Gleeson et al. (2016). Rate of change: de Graaf et al. (2017)
Lakes	102,424**	−1,975	C	Total storage: Messager et al. (2016). Rate of change: WCRP (2018)
Soil moisture	16,500	−519	C	Total storage: Shiklomanov (1993). Rate of change based on Deng et al. (2020)
Dam reservoirs (large and small)	11,270	7,160	H	Total storage: Frederikse et al. (2020). Rate of change: WCRP (2018); total small dam reservoir is estimated at 1,873 BCM with an estimated increase of 1,336 BCM (Lehner et al., 2011)
Forests	9,816	−1,029	H	Total storage based on forest area and Wada et al. (2017). Rate of change based on forest loss from FAO (1990), FAO and UNEP (2020), and Wada et al. (2017)
Wetlands	9,300	−3,784	H	Total storage based on wetland area and Wada et al. (2017). Rate of change: Darrah et al. (2019)
Paddy fields	836	150	H	Total storage and rate of change based on paddy area from Davidson et al. (2018) and this study
Total	**10,704,146**	**−15,704**		

Notes: BCM = billion cubic metres. Antarctic and Greenland ice sheet contributions have not been included.

* Assuming 46 percent of groundwater is freshwater as per Gleick (1996). ** Assuming 56% of lake water is freshwater as per Messager et al. (2016).

Source: modified from McCartney et al. (forthcoming).

Minding the storage gap

Better understanding about the storage gap at the country, river basin, and local levels is needed to identify solutions. For people and communities, what is most relevant are not global changes but the changes in storage that affect local water resources and the river basins in which they live or where their agricultural products (food, feed, fibre, and fuel) are produced. In highly populated basins where reserves in both natural stores (e.g. glaciers, soil moisture, and wetlands) and human-made stores (e.g. reservoirs) are declining simultaneously, water resource management is increasingly difficult. At the same time, with increases in population pushing for greater storage availability (e.g. more flood storage, hydropower, assured supplies for drinking and irrigation), for many countries the widening storage gap has serious implications for system resilience, water-related risks, and long-term sustainability. Therefore, countries need to move towards integrated solutions that consider a wider array of storage types, and develop ways to operationalise such systems to more reliably and sustainably deliver services to society.

Understanding storage as a provider of services

In an integrated approach, storage is conceptualised as a provider of services rather than a collection of individual storage facilities. An approach based on service delivery clarifies the relationship among storage, biophysical processes, socio-economic interests, and human well-being. Here, services are defined broadly to include drinking and irrigation services, ecosystem functions, and flood and drought protection, among others. Taking a services approach allows a 'like for like' comparison of different types and combinations of storage. It also becomes possible to articulate storage service performance parameters (e.g. volume delivered, reliability) that can then be used to define and evaluate which system or portfolio of storage solutions might best meet various needs.

Investing in storage solutions also requires a clearer picture of the advantages and disadvantages of different storage types and how they interact. As the data in Table 4 make clear, dams contribute only a small proportion of total global water storage. However, they often become the focus during policy responses and debates on increasing storage. Nature-based solutions are quantitatively far more significant, but it is less clear how to invest in or 'manage' the water stored in nature. Similarly, while groundwater is collectively a vast resource, its local performance parameters are unclear, particularly in data-scarce environments, leading to sustainability challenges. To put storage solutions into practice, the best complement of storage types should be identified and integrated to deliver different services. The idea of optimising water storage development through diversifying its options goes back to Keller et al. (2000). Van der Zaag and Gupta (2008) further examined options for developing dispersed storage throughout a basin. Integrating these storage types not only gives the planner more options to consider, but also pushes the planner to better understand the relationships between them. Water accounting tools can also be used to better understand how different stores of water interact, are co-dependent, and can be used in concert to achieve certain service objectives. This will be critical in understanding how to integrate different storage types and in determining the overall system effectiveness for delivering services.

Putting integrated storage solutions into practice

Storage is more than dams. Despite the recognised need for increased water storage, there is a continued debate about the most appropriate types of intervention (McCully and Pottinger, 2009). Though it has been 20 years since the World Commission on Dams Report (WCD, 2000), the debates on dams will continue into the far future. Part of this relates to a plurality of voices and often irreconcilable differences in values (whether from an economic, environmental, social, historical, political, or even cultural perspective). Moreover, given the public budget constraints that many governments face and competing demands from other sectors, it is increasingly difficult to prioritise dams. At the same time, there may be no alternatives for the different services that storage, more broadly speaking, provides. In the end, dams are controversial because they are so consequential – unintentional or otherwise, negative or positive. The question is whether small distributed infrastructure, nature-based approaches, landscape restoration, or a blend of grey and green solutions will be more effective (technically, economically, environmentally, socially) and publicly accepted in delivering society's needs.

A better understanding of the effectiveness of natural storage is needed as well as important co-dependencies. In principle, natural storage (or more broadly nature-based solutions – NBS) has the potential to tackle many water resource management challenges, simultaneously contributing to both climate mitigation and climate adaptation and delivering multiple co-benefits for people and nature (UN, 2018). For example, soil and water conservation measures in upper catchments are often promoted to reduce soil erosion and increase groundwater storage, reduce sedimentation of downstream reservoirs, and help protect downstream communities from flooding. At the same time, such interventions may also increase carbon sequestration and protect biodiversity (TNC, 2015). Because of their potential climate co-benefits, NBS have been broadly endorsed by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019), the Intergovernmental Panel on Climate Change (IPCC, 2019), and the Global Commission on Adaptation (GCA, 2019). However, many important questions remain regarding the technical and cost effectiveness of many proposed NBS (Seddon et al., 2020). For example, while it is widely recognised that natural ecosystems (e.g. forests, wetlands, and grasslands) influence how water is cycled and stored in a basin, there is little quantitative information on the magnitude of these impacts (Bruijnzeel, 1996; Bullock and Acreman, 2003) and, more importantly, how this could be predicted in 'new' areas to aid planning and design. There is also the risk that what might make sense from a land reclamation point of view may in fact exacerbate water shortages (Zhang et al., 2015). The picture is further complicated by the fact that natural systems are dynamic – changing over time as plants grow, senesce, and die, and as natural processes alter landscapes – and so effectiveness also changes over time (i.e. between seasons and between years) (McCartney et al., 2013b). This understanding is needed to more effectively integrate natural and built storage facilities for operational purposes.

Operationalising resilience for integrated storage systems is a challenge. Engineers have long used resilience and reliability criteria for built water resource systems (Hashimoto et al., 1982). However, in the context of combined grey and green approaches and larger cross-discipline systems (e.g. food and energy systems), operationalisation of these concepts can be unwieldy. For example, by integrating natural and built storage types, each with different performance and service characteristics and uncertainties, determining and designing the overall system capacity for improved resilience becomes more difficult. Adaptive management will be critical to operationalising resilience: shifting to supporting decision-making under uncertainty and emphasising risk management and preparedness over a range of possible futures. Because of the presence of unavoidable (or 'deep') uncertainty, the goal is to identify 'robust decisions' that have satisfactory performance across a wide range of plausible futures, rather than performing optimally over a historical period or a few scenarios (Grove and Lempert, 2007; Lempert et al., 2003). One of the key design principles for such robust decisions is to make operating plans that are flexible and can be adapted over time in response to how the future unfolds (Haasnoot and Middelkoop, 2012; Walker et al., 2013). Integrated storage systems can provide this greater flexibility.

Storage is part of a larger system of water resource management tools for managing resilience. Storage systems are one tool that water managers have for providing numerous services to societies (present and future) as well as for managing the resource (e.g. in relation to floods, droughts, and water quality) to protect communities. Other tools include economic and policy instruments, demand-side measures, regulatory instruments, and stakeholder and participatory approaches. While demand-side measures will often be cheaper and more rapidly scalable (e.g. see Cape Town's day zero response), there are limits to how much can be achieved. On the supply side, water transfers, desalination, and reuse are all viable alternatives to storage, but are in turn limited by cost, feasibility, scale, and so on. In managing extremes, whether droughts or floods, there may also be limits to what can be achieved using soft approaches such as improved forecasting, early warning, and better preparedness. Generally, for most countries, some combination of tools and approaches will be needed to reduce risks and to make societies and economies more resilient.

Strong governance arrangements on integrated storage management are needed. There is broad agreement on the importance of governance in water management (OECD, 2015). Given the role that storage of all types plays in generating multiple benefits (not only in strict economic terms), how these benefits are shared requires clear and transparent arrangements. This is already a challenge with traditional single-facility storage units that often provide multiple services (e.g. irrigation, flood control, hydropower, fisheries) and draw on the responsibilities of multiple parts of government (both horizontally across traditional sector boundaries and vertically from national to local levels) and a wide range of stakeholders. Thus, integrating different types of storage may complicate existing governance arrangements and require even more coordination and collaboration across multiple governance systems. For example, in integrating the use of nature-based solutions a wider set of actors may be involved in design, planning, management, and decision-making than before (e.g. departments of land management, environment, forestry). Moreover, built storage will often have a clear 'owner', while this may be less apparent with natural storage. One also cannot underestimate the varying needs of local communities, which will adapt storage solutions to provide additional services not previously considered (van Koppen et al., 2006) or which may adopt land-use behaviours that have storage implications. Because of the widening functionality possible with a more integrated approach to storage, designing the institutional arrangements for its proper management (e.g. rules for allocation of storage use, benefit-sharing arrangements) is not a trivial task. Simultaneously, the process of building these arrangements in a participatory manner is as critical as the mechanisms themselves (i.e. converting stakeholders into 'shareholders').

Integrated storage approaches require more inclusive stakeholder engagement. The importance of participatory approaches to the identification, selection, and design of storage solutions is well documented. By bringing all stakeholders to the table, the necessary (though not sufficient) condition for minimising conflicts and competing interests is met. This becomes even more critical in the context of more integrated approaches that will draw on a wider array of interests. For example, with natural storage, land ownership interests may be more varied compared with built storage on government land. Thus, getting public acceptance will require a higher degree of coordination, collaboration, and recognition of more complex human–nature interactions. Decision-making processes and mechanisms to design and operate across built and natural environments will also need to be inclusive and empower the most marginalised in the watershed (e.g. the poorest, women, children).

More innovative financing is needed. Rozenberg and Fay (2019) estimate that with the right policies in place, low- and middle-income countries will need to spend 4.5 percent of GDP per year to meet the infrastructure-related SDGs. Achieving the water-related SDGs will require investment of US$6.7 trillion in the water sector by 2030 (Oxford Economics and Global Infrastructure Hub, 2017). Thus, the financing challenges across all of society's development aspirations are enormous. At the same time, globally, NBS currently account for less than 5 percent of total investment in water-related infrastructure (UN, 2018). Prioritising limited public budgets across these needs will be driven by political, social, economic, and financial criteria. More integrated storage solutions will likely be funded from a mix of public and private sources. For some storage services (e.g. water supply and sanitation, irrigation, hydropower), a wider range of financing modalities is possible, including from commercial and private sources. For other storage services, particularly those with NBS components, the benefits may be more public in nature (e.g. flood control, biodiversity, water quality) and thus largely funded by government. However, environmental and socio-economic co-benefits (e.g. biodiversity, carbon sequestration, fisheries, recreation, and even job creation and livelihoods) may be eligible for 'green' financing approaches (e.g. green bonds). In the end, given that integrated storage will provide multiple services, there is an opportunity to package funding and financing proposals in such a way that takes advantage of the different kinds of benefits being generated.

A new agenda for integrated storage

Storage is a foundational element of water resources management and critical to supporting resilient development. The importance of storage systems as a tool to deliver services and protect society (from floods and droughts, and poor water quality) will only grow in the context of demographic, societal, and climate changes. With many competing demands for water and more variable supplies, well-integrated storage systems (with a proper balance between green and grey approaches) will provide water managers with greater options, flexibility, and adaptability to help put countries on more resilient development pathways. There are many well-known practical barriers to effective water resources management (e.g. institutional dimensions, political economies, difficulties with valuing water) that will remain. Nonetheless, the opportunities that a wider perspective on storage brings are clear.

GWP and the International Water Management Institute (IWMI) have made calls to action on adaptation to climate change. Both the 2020–2025 GWP strategy (Mobilising for a Water Secure World) and the 2019–2023 IWMI strategy (Innovative Water Solutions for Sustainable Development) recognise the importance of water in adapting and building resilience to climate change. Urgent action on integrated water storage will be essential to supporting these aims.

Moving forward, to support this agenda several critical steps are needed:

- Developing a framework for rethinking water storage as an integrated service: While 'integrated water resource management' has long been accepted, it is not clear how to pragmatically develop and manage different (albeit often co-dependent) storage components, each with its own performance and service characteristics, as an integrated system. Such a framework will be helpful for policy-makers, financiers, and planners to guide future investment as well as manage and protect existing storage systems in a practical and cost-effective way.

- Improving the inventory of water storage and its attributes: There have been many positive developments in establishing the scale, nature, and locations of various storage types. However, there remains more to be done in better understanding how much storage exists of different kinds, how it is changing over time, and its various attributes (e.g. live storage available for different purposes) across the globe at the country level. Complete characterisation of entire storage systems (both built and natural assets) within a basin framework remains limited. Perhaps more importantly, how this storage is currently being used or the implicit functions it serves are not well understood. A better understanding will require more local-scale analyses at country, basin, and sub-basin levels.

- Unpacking the effectiveness of nature-based solutions: Though the engineering profession has tested approaches to determining the effectiveness of built infrastructure, more analysis is needed with respect to the effectiveness (whether from technical or economic perspectives) of various nature-based storage options. Effectiveness must be evaluated from both the longer-term perspective and at a broader spatial scale. This also requires a better understanding of the interactions and co-dependency between natural and built environments.

- Assessing the socio-economic costs and benefits of integrated storage systems: The use of traditional cost–benefit analysis for water infrastructure is well established, as are the critiques of such methods for capturing full economic values. Approaches have been developed to estimate the broader macro-economic impacts of single-facility storage (including distributional and equity issues), particularly for large dams (e.g. Bhatia et al., 2007; Robinson et al., 2008). At the same time, the economic costs and benefits of natural storage and green infrastructure are still being developed. These are challenging exercises given the methodological difficulties with assigning values to some of the, mostly positive, environmental and social co-benefits. Comprehensive economic valuations of integrated natural and built systems are less well developed.

- Developing innovative approaches to water storage operation: With advances in sensor and space technologies and artificial intelligence and machine learning, there are opportunities to better manage and operate existing storage systems, both natural and built (i.e. to reduce risks and maximise reliability). This includes using satellite imagery to better monitor and predict catchment sediment yields and dam safety risk. Moreover, advances in materials science may introduce greater flexibility in approaches (e.g. removable rubber dams) and in cost (e.g. new concrete technology, modular construction technologies).

- Optimising integrated storage planning and operations: With different types of storage available, each with different characteristics (e.g. volume, feasibility, adaptability, controllability, reliability, vulnerability, sphere of control, cost, and sustainability), analytical tools are needed to examine from a systems perspective (e.g. basin) how different combinations of storage types can achieve various service objectives. A key feature of these tools will be the interactions between natural and built storage. Developing such a portfolio approach can help to better articulate risks across different performance metrics and users. Such tools will also be important in examining costs and benefits, to support the planning and optimisation of future storage needs. These kinds of tools are needed by countries, cities, companies, communities, and other stakeholders.

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