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202

Working Paper

Change in Global Freshwater Storage

Matthew McCartney, William Rex, Winston Yu, Stefan Uhlenbrook and Rachel von Gnechten

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Contents

Acronyms and Abbreviations

AD	Anno Domini
AR6	IPCC Sixth Assessment Report
BCE	Before the Common Era
FAO	Food and Agriculture Organization of the United Nations
GRACE	Gravity Recovery and Climate Experiment
GRanD	Global Reservoir and Dam
GWD	Groundwater depletion
ICOLD	International Commission on Large Dams
IPCC	Intergovernmental Panel on Climate Change
MW	Megawatt

Summary

Freshwater in both natural stores (i.e., glaciers, permafrost, groundwater, lakes, wetlands, and soils) and man-made stores (i.e., small and large reservoirs, and paddy fields) is critical for coping with spatial and temporal variations in water supply and demand. Its importance has grown as human populations have risen and socioeconomic development advanced. As a major component of many national adaptation strategies, the importance of water storage will continue to increase as the impacts of climate change become more pronounced. However, in large part because of the complex distribution over large spatial scales, and difficulties in monitoring, the aggregate volumes of water in terrestrial stores and the rates at which they are changing have, until recently, remained largely unknown. Recent advances in Earth observation and computer modeling enable greater disaggregation and better quantification of different storage elements. Based on literature and extrapolation, this paper provides a summary of estimates of different components and trends in terrestrial water storage. Such estimates are a useful starting point for more strategic thinking about how to manage and protect the Earth's freshwater sources in the future. Results indicate that, at the global level, direct human impacts on water storage remain very small compared to the total volumes stored, but are now approximately the same order of magnitude as climate-induced changes. Cumulative reduction in terrestrial water storage from 1971 to 2020 is estimated to be of the order of 27,079 Bm^3 (more than annual total global freshwater use by humans). Excluding ice caps, the greatest depletion is in mountain glaciers (8,666 Bm^3), groundwater (7,041 Bm^3) and wetlands (3,920 Bm^3). Although these changes are insignificant at the global scale, human impacts on 'operational' freshwater storage (i.e., the proportion of water storage that is sustainably utilizable by people) are much more significant. A conservative estimate is that there has been a decrease of more than 3% in operational freshwater storage since 1971. Declining water storage is a major contributor to local/regional water crises that ultimately threaten billions of people and many ecosystems worldwide. In many places, both natural and man-made water storage are declining simultaneously and exacerbating water stress. Decades of degradation of lakes, wetlands and soil, and sedimentation of reservoirs, as well as overabstraction of groundwater complicate future water resources management, reduce adaptive capacity, and undermine the resilience of 'thirsty' societies that are increasingly under threat from the impacts of climate change and increasing variability in freshwater availability. Actions to stop and reverse the loss of water from both natural and man-made water storage would help enhance water security, and buffer the negative impacts of multiple pressures, not only climate change, on ecosystems and society.

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Introduction

Freshwater storage is a cornerstone of socioeconomic development (Grey and Sadoff 2007). Ancient civilizations arose in locations where it was possible to exploit natural water sources, including rivers, lakes and groundwater, and were directly dependent on natural water stores. For example, the Indus Valley Civilization, dating back to the 3rd millennium before the common era (BCE), exploited water in rivers of the Indus Valley and so, in part, relied on meltwater stored in the headwater glaciers and snow cover (Amrawat 2019). Other civilizations have depended on increasingly sophisticated water stores, including dams, cisterns and ponds, as well as methods for harvesting rainwater, floodwater, groundwater and natural springs. For instance, the Angkor Civilization (Anno Domini [AD] 800 to 1400) developed an extensive and complex water management system that connected the natural lake of Tonle Sap to large man-made reservoirs and made use of groundwater (Kummu 2009).

Today, total human water use (green, blue and grey water) is estimated to be approximately 24,000 billion cubic meters (Bm^3)y^{-1} globally, of which approximately 18,720 Bm^3y^{-1} is green water (i.e., evapotranspiration from soils and plants). Blue water consumption (i.e., evaporation from abstracted/withdrawn surface water and groundwater) is estimated to be in the range 3,800 to 5,000 Bm^3y^{-1} (16–21%) (Abbott et al. 2019). To access water, all societies rely on water storage in one form or another and, even with sophisticated technology, remain dependent on natural water stores, whether they are aware of it or not.

The global distribution of freshwater storage is changing. Rising temperatures affect the total amount and the seasonality of water stored in snow and glaciers, as well as rates of evaporation. Increasing variability in precipitation and runoff will affect the movement of water between soils, groundwater, rivers and lakes. In addition, degradation of lakes and wetlands, and overexploitation of groundwater deplete natural water stores. Conversely, the construction of dams and man-made wetlands, including paddy fields, alters volumes stored in man-made water stores and enables human appropriation of freshwater.

Globally, climate change is intensifying the hydrological cycle, enhancing seasonality, increasing variability in water availability, and increasing the severity of very wet and dry periods (IPCC 2021). Simultaneously, volumes of water stored (in both natural and anthropogenic water stores) are declining. In some places, this is resulting in a perceived 'gap' in water storage; potentially insufficient water storage for society to cope during periods of shortage, or increased vulnerability to rapid runoff and floods (Yu et al. 2021). Globally, hundreds of millions of people are affected adversely by water scarcity and approximately 1.2 billion people live in areas where agriculture – the largest human use of water - is severely affected by water scarcity and shortages (FAO 2020).

Against this backdrop, there is a need to monitor and better understand trends and anthropogenic impacts on all forms of water storage. This paper presents an integrated assessment (based on a literature review) of global change in different terrestrial water stores from 1971 to 2020. Inventories of most forms of water storage are not systematically produced at national or regional levels. Therefore, estimates had to be derived from a wide variety of sources utilizing a wide range of estimation methods, including modeling. In many cases, estimates have been derived from the large body of literature pertaining to changes in sea level brought about, in part, by changes in terrestrial water storage. Because sea level rise integrates the impact of changes in terrestrial water storage, in conjunction with thermal expansion, it can be used to estimate an upper bound and provides a partial validation of estimates of global change in terrestrial water storage.[1]

This paper describes the main terrestrial water stores, their contribution to total water stored and the trend in each type of water storage (see section *Water Storage*). The assessment indicates widespread human-caused changes in water storage (both positive and negative). The total change in terrestrial water storage over 50 years (1971-2020) is estimated (see section *Aggregate Freshwater Storage and Cumulative Change*) and broad implications are discussed.

[1] Since 1900, global mean sea level has increased between 160 mm and 210 mm. Approximately half of this rise is due to thermal expansion and the other half is due to increased inflow of water, primarily from melting ice, but also from other terrestrial water stores (WCRP 2018).

Water Storage

Ice Sheets and Glaciers

Water stored as ice, in the Antarctic and Greenland ice caps and in mountain glaciers – approximately 30 million Bm^3 (Table 1), represents the largest store of freshwater on the planet. The large ice sheets are mostly inaccessible to people, but seasonal meltwater from glaciers, particularly in the Andes and Hindu Khush Himalayan region, contributes to river flows that sustain downstream ecosystems and the livelihoods of billions of people (Mark et al. 2015).

Table 1. Water stored as ice.

Store	Volume (Bm^3)
Antarctic ice sheet$^+$	26,500,000
Greenland ice sheet$^+$	2,850,000
Mountain glaciers^{++}	158,000

Sources: $^+$ WCRP 2018; $^{++}$ Farinotti et al. 2019a.

The importance of glacial melt in the overall water resources of a river basin depends not only on the extent and ice volume of the glaciers but also the basin hypsometry, relative glacier area, climate, and the downstream demand for water. With the exception of the Indus, for many large basins (e.g., the Ayeyarwady, Mekong, Ganges, and Brahmaputra), the contribution of glacial melt to total river flow is small, but they provide an important buffer and can be particularly significant in the dry season and in dry years. In many upstream rivers (e.g., headwater tributaries), glaciers play a crucial role in water supply. For example, in the Andes, the number of users relying continuously on water resources with a high (> 25%) long-term average contribution from glacial melt is low (391,000 domestic users, 398 km^2 of irrigated land, and 11 megawatts [MW] of hydropower production), but this reliance increases significantly during periods of drought (up to 3.92 million domestic users, 2,096 km^2 of irrigated land, and 732 MW of hydropower production in the driest month of a drought year) (Buytaert et al. 2017).

Accelerated melting of glaciers, because of climate change, will in time likely reduce the capacity of basins to buffer variation in precipitation. However, the overall impact on water resources is difficult to predict because of likely changes to other components of the water budget such as groundwater recharge and discharge, seasonal snowmelt and rainfall seasonality (Mark et al. 2015). Although, globally, glaciers are melting, a few are advancing (i.e., growing) as a consequence of local climatic conditions (e.g., Khazendar et al. 2019). In many cases, this is considered to be a temporary phenomenon and does not contradict the globally observed net reduction of ice mass. A recent study predicted that by 2050, melting glaciers could create ice-free basins in which dams could feasibly be built to create reservoirs (i.e., effectively replacing some of the lost volume of ice) with a total storage capacity of approximately 355 Bm^3; approximately half the current annual runoff from the basins (Farinotti et al. 2019b).

Prior to the advent of the Gravity Recovery and Climate Experiment (GRACE) satellite system, no globally complete observational dataset existed for estimating changes in glacier mass. Consequently, past studies had to rely on spatial interpolation and extrapolation of measurements on individual glaciers. A review of studies (including those using GRACE) provides an ensemble estimate of mountain glacier change of 5,868 ± 460 Bm^3 for the period 1993-2018 and 9,625 ± 1,203 Bm^3 for the period 1961-2016 (WCRP 2018). Other studies have estimated recent Greenland and Antarctica melting as 3,474 ± 281 Bm^3 (1992-2108) and 2,708 ± 140 Bm^3 (1992-2017), respectively (The IMBIE team 2018, 2020). A more recent study estimated the Antarctic cumulative ice melt as 5,019 ± 722 Bm^3 (1979-2017) (Rignot et al. 2019). Another study estimated that Greenland ice melt was 4,947 ± 402 Bm^3 in the 46 years from 1972 to 2018 with half the volume melted occurring in the last 8 years (Mouginot et al. 2019).

Although large amounts of storage are being lost from the high latitude ice caps, the shrinking of high altitude, mountain glaciers is the most significant in terms of direct water resource implications for people. Based on past studies, we estimate that over the past 50 years, loss of ice from glaciers is of the order of 8,666 Bm^3 (173 Bm^3y^{-1}). The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) states that "human influence is *very likely* the main driver of the global, near-universal retreat of glaciers since the 1990s" (IPCC 2021). This melting of glaciers, in combination with snowmelt earlier in the season, increases and changes the timing of streamflow with many consequences for downstream communities.

Permafrost (Underground Ice)

Found to depths of 650 m, the total area of permafrost (underground ice) is estimated to be about 21 million km^2 primarily over the circumpolar regions of northeast Europe, north Asia, northern Canada and fringes of Greenland, but also in the mountains of Asia, Europe and South America. Permafrost comprises perennially frozen soil, rock and ground ice. Ground ice occurs both in the pores of the soil matrix and also as massive bodies of ice (lenses and wedges), often meters in width and depth and tens of meters in length (Blunden and Arndt 2019). In some places, an active upper layer thaws and freezes seasonally. Due to the lack of data, current impossibility of monitoring by satellites, and existence of relatively few studies, the water stored as permafrost can only be estimated, but is believed to be about 300,000 Bm^3 (Shiklomanov and Rodda 2003).

Human populations are generally sparse in regions where permafrost occurs and there are no records of ground ice being exploited directly for significant quantities of water. The contribution of the active layer melt to groundwater and runoff generation and hence liquid water resources is unknown but believed to be minimal at the global scale. However, because of climate change, permafrost temperatures are rising faster than air temperatures in many places. Though absolute values are highly heterogeneous across the Arctic, permafrost temperatures have risen on average by 1.5-2.5 °C in the last 30 years (Bykova 2020). As a result, shallow permafrost layers are melting and, notwithstanding the damage this causes to ecosystems and infrastructure, it is speculated that they may become more important for water resources in the future (Hoelzle et al. 2017).

Groundwater

With the exception of frozen water in ice and glaciers, groundwater is by far the world's largest distributed store of freshwater. Total global reserves, in the upper 2 km of the continental crust, are estimated to be between 15.3 million Bm^3 (Alley et al. 2002) and 22.6 million Bm^3 (Gleeson et al. 2016), of which only between 0.1 million Bm^3 and 5 million Bm^3 has residence times of less than 50 years (Ajami 2021). Based on earlier estimates of total groundwater volume, it has been estimated that about 54% of the Earth's groundwater is saline and only about 46% is freshwater (Gleick 1996). Total fresh groundwater reserves are about 100 times larger than fresh surface water stores, excluding glaciers and ice sheets (Fitts 2013), but the renewable and readily available proportion of groundwater is distributed heterogeneously and is only 1-5% (i.e., at most 0.25 million Bm^3) of total groundwater resources (Richey et al. 2015).

In many places, groundwater has historically supplied domestic water requirements in human settlements. It was the accessibility of groundwater through dug wells, at springheads and in seepage areas, which, for thousands of years, controlled the extent of human settlements beyond major river valleys. According to one estimate, more than two billion people worldwide currently depend on groundwater for domestic supplies (Ajami 2021). Also, groundwater contributes to 44% of irrigated food production worldwide (WLE 2017).

In part, as a consequence of the availability of inexpensive pumps, drilling technology, increased energy access, and agricultural production and food procurement policies (including subsidies), annual global abstraction of groundwater increased from 100–150 Bm^3 in 1950 to 950–1,000 Bm^3 in 2000. Ninety percent of groundwater abstracted is used for irrigation, particularly in Asia (Shah et al. 2007). Much of this high groundwater use is concentrated in dryland areas of Bangladesh, China, India, Iran, Pakistan and the United States of America (USA), which account for well over 80% of global groundwater abstractions. In contrast, in sub-Saharan Africa, it is estimated that although 50-75% of the population relies on shallow groundwater for domestic supplies, deeper resources are currently largely underutilized, and most countries currently exploit less than 5% of national sustainable groundwater yield (Cobbing and Hiller 2019).

In many places in Asia, the Middle East and North Africa, and North America, groundwater is being pumped beyond the renewable rate and reserves of the resource are being depleted. It is estimated that 20% of the world's aquifers are overexploited (Gleeson et al. 2016). Groundwater depletion (GWD) represents a loss in water stored, but because in most cases (though not all) the aquifer remains and would be refilled if withdrawals were curtailed, it does not represent a loss of storage 'capacity' *per se*.[2] Nevertheless, in places where storage capacity is relatively small or where abstractions are large (e.g., parts of India, China and the USA), GWD results in severe groundwater stress, which seriously threatens the sustainability of groundwater resources and undermines resilience of the system (Richey et al. 2015). The direct effects of GWD are falling groundwater levels, increased pumping costs, land subsidence, reduced baseflows to rivers and declining water quality (including saltwater intrusion in some areas), with severe implications for ecosystems and people in many places.

Döll et al. (2014) used hydrological modeling, well observations and GRACE satellite gravity anomalies to estimate a global GWD of 113 Bm^3y^{-1} over the period 2000–2009. This value represents the impact of human groundwater withdrawals only and does not consider the effect of climate variability on groundwater recharge and hence storage. Another study estimated global GWD to be 145 ± 39 Bm^3y^{-1} over the period 1991–2008 based on measurements of changes in groundwater storage from *in situ* observations, calibrated groundwater modeling, GRACE satellite data and extrapolation to unobserved aquifers (Konikow 2011). Wada et al. (2016) estimated the changes in GWD from 7.22 ± 1.44 Bm^3y^{-1} in 1900 to 97.5 ± 14.44 Bm^3y^{-1} in 2000.

Depleting groundwater resources are a major concern in many parts of the world. We estimate that, over the past 50 years, the aggregate removal of water from groundwater storage is of the order of 7,041 Bm^3 (141 Bm^3y^{-1}), primarily as a consequence of the expansion of irrigated agriculture. Changing glacier and snowpack melting will affect the recharge of aquifers in mountain valleys. In coastal aquifers, seawater intrusion exacerbated by groundwater abstraction is a problem in some places (e.g., the Asian mega deltas).

[2] Exceptions occur where 'fossil' groundwater is being abstracted (e.g., in the Middle East and North Africa), where reserves cannot be renewed easily and abstraction results in ground subsidence and/or saltwater intrusion (e.g., in deltas, coastal aquifers). In these cases, changes are irreversible and abstractions translate into a reduction in storage capacity (Minderhoud et al. 2019).

Lakes

Lakes store the greatest mass of liquid water on the terrestrial surface (Table 2). They provide domestic water for millions of people globally and are an important source of water for irrigation, industry and cooling water in thermal power plants. It is estimated that lakes cover 2.67 million km^2 (i.e., 1.9% of global land area) and, excluding reservoirs, contain a total water volume of 182,900 Bm^3, approximately 44% of which is saline (Messager et al. 2016). Natural interannual variability results in significant changes in storage, and the storage changes over annual and decadal time frames. In addition, human withdrawals – primarily for irrigation – can exert sustained reductions in inflows and have led to significant changes in many saline and freshwater lakes (e.g., the Caspian Sea, Aral Sea, Lake Urmia and Great Salt Lake). When lakes are severely desiccated, direct economic losses can be significant, due to reduced fisheries and loss of other ecosystem services. Also, the dust blown from exposed lake beds can harm human health and agriculture (Wurtsbaugh et al. 2017).

Table 2. The world's largest lakes by volume.

Name	Volume (Bm^3)	Country
Caspian Sea	78,200	Azerbaijan, Iran, Kazakhstan, Turkmenistan and Russia
Baikal	23,600	Russia
Tanganyika	18,900	Tanzania, Democratic Republic of the Congo, Burundi and Zambia
Superior	11,600	Canada and USA
Malawi	7,725	Malawi, Mozambique and Tanzania
Vostok	5,400 ± 1,600	Antarctica (under the ice sheet)
Michigan	4,920	USA
Huron	3,540	Canada and USA

Source: Misachi 2019.

In the past century, perhaps the greatest contributor to change in the water stored in lakes was the Caspian Sea (Milly et al. 2010), where the water level exhibits substantial oscillations attributed to meteorological, geological and anthropogenic factors (Chen et al. 2017). The overall change in the Caspian Sea, including both surface water and groundwater storage variations, is estimated to have been about 1,235 Bm^3 from 1900 to 2014, with greater contributions in recent years (i.e., 271 ± 7.23 Bm^{3}y^{-1} from 1995 to 2015 and 197 ± 7.22 Bm^{3}y^{-1} from 2002 to 2014) (WCRP 2018). Additionally, between 1960 and 1990, water storage in the Aral Sea Basin declined at a rate of 64 Bm^{3}y^{-1} due mostly to upstream water diversion for irrigation (Perera 1993; Vörösmarty and Sahagian 2000). The total decrease between 1951 and 2000 is estimated to be about 500 Bm^3 (Pokhrel et al. 2021). The decline in the Aral Sea has continued more slowly in recent decades, with an annual rate of 6.04 ± 0.082 Bm^{3}y^{-1} measured from 2002 to 2014 (Schwatke et al. 2015). In recent years, efforts have been made to improve water flow into the northern portion of the sea, which is expanding (Chen 2018).

The aggregate reduction in lake water storage is estimated to be 704–1,126 Bm^3 between 2002 and 2015 (WCRP 2018), and we estimate a reduction of approximately 1,975 Bm^3 (i.e., 40 Bm^{3}y^{-1}) between 1971 and 2020.

The degradation of lakes is a worldwide phenomenon, threatening ecosystem functioning and a multitude of ecosystem services (not just water provision). Past alteration of large lakes reduces their capacity to resist new threats. Degradation of water quality will likely continue because of the cumulative impact of ongoing local pressures, synergies between stressors, and the imposition of global stressors (e.g., climate change and invasive species). Although all the consequences for lakes and their ecosystem services are difficult to fully predict, the alteration of lake ecosystems is causing a major concern among freshwater scientists (Jenny et al. 2020).

Reservoirs

Since 1950, humans have constructed more than 57,000 large dams (taller than 15 m) globally (ICOLD 2020). Man-made reservoirs now cover approximately 0.26 million km^2 (i.e., 0.2% of the global land area) (Messager et al. 2016). The construction of these dams has helped secure water supplies and fuel economic development (Grey and Sadoff 2007). The International Commission on Large Dams (ICOLD) database does not geo-reference dam locations and it contains some dams located at the outlets of natural lakes (e.g., Lake Victoria), where the dams regulate and may have added to, but have not created, the full storage volume. It is not possible to identify such dams explicitly from the ICOLD database, although at least in some cases (e.g., Lake Victoria), the difference between the natural lake storage and the storage created by the dam is given. Nevertheless, most recent efforts to estimate global terrestrial water storage have utilized the Global Reservoir and Dam (GRanD) database, which has geo-referenced locations and distinguishes between reservoirs and lake control (Lehner et al. 2011). It comprises 7,320 geo-referenced dams with a total storage capacity of 6,116 Bm^3 and 756 Bm^3 of lake control storage for a total storage volume of 6,881 Bm^3. Of the total storage capacity, 3,603 Bm^3 has been constructed since 1970. The GRanD database contains data of the largest dams, but this is certainly an underestimate of the total storage behind large dams.

Large dams are used to store water for many purposes, including irrigation, hydropower, water supply, flood control, navigation and recreation. The ICOLD database suggests that the construction of large dams accelerated significantly after World War 2 and peaked during the 1980s, before declining significantly since then. While many dams are multipurpose, irrigation is the most common primary purpose of large dams. Hydropower dams are, on average, significantly larger than other types of dams, with considerably more storage. While the rate of dam construction has slowed from historical peaks, a significant number of large dams are still being developed and are at various stages of planning (Zarfl et al. 2015). However, given that dams – and particularly large dams – are based in naturally occurring features, there are inherent limits to the growth of large dams from a water storage perspective. Furthermore, many large dams are now relatively old. In the USA, 80% of dams, and a significant proportion throughout the rest of the world, are more than 50 years old. As dams age, their structural integrity may decline and the rationale for existence may become redundant. As a result, though only a relatively recent phenomenon, there is increasing interest in decommissioning dams, including some large dams (Perera et al. 2021).

The largest man-made reservoirs store significant but, in comparison to natural lakes (see section *Lakes* above), relatively small volumes of water (Table 3). The Grand Ethiopian Renaissance Dam on the Blue Nile in Ethiopia, the largest reservoir currently under construction in the world, will store 74 Bm^3 of water when filled over the next few years. Net reservoir capacity is still believed to be increasing in most regions of the world, but it is declining in many individual river basins because of the slowdown in construction as well as the loss of storage due to sedimentation and decommissioning. As a result of rising population, per capita storage capacity of reservoirs is believed to have been declining globally since about 1990 from approximately 1,000 m^3 per person to approximately 850 m^3 per person in 2010 (Wisser et al. 2013).

In addition to large dams, huge numbers of small dams, ponds, cisterns, tanks and other micro-storage facilities have been constructed to store water, primarily for small-scale irrigation but also for domestic water supply and other uses. A recent study estimated that widespread adoption of small-scale water harvesting technologies, including storage of runoff and rainfall, could increase crop production by 60-100% in the cropland areas of Uganda, Burundi, Tanzania and India (Piemontese et al. 2020).

There are no global datasets quantifying the area or storage capacity of small reservoirs. However, in dry areas of India, an estimated 120,000 small reservoirs supply irrigation water to more than 4.12 million hectares (Mha) (Wisser et al. 2010). Small reservoirs are also widespread in Africa, providing a range of benefits, including domestic water supply, irrigation, livestock watering and fisheries (Saruchera and Lautze 2019). A study conducted in the Upper East Region of Ghana estimated that storage in 500 small reservoirs was 185 Mm^3 (Liebe et al. 2005). It is known that there are several million small reservoirs in the USA alone (Renwick et al. 2005). Also, on the basis of statistical distributions, one study estimated that globally there are about 2.8 million reservoirs with a surface area larger than 0.1 ha and 16.7 million small reservoirs with a surface area larger than 0.01 ha (Lehner et al. 2011). It is estimated that these small reservoirs have a cumulative storage capacity of 1,873 Bm^3 (Lehner et al. 2011). If 50% of this small reservoir storage was created between 1971 and 2020, that equates to 937 Bm^3.

Table 3. The world's largest man-made reservoirs.

Reservoir	Volume (Bm^3)	Country
Lake Kariba	180.6	Zambia/Zimbabwe
Bratsk Reservoir	169.0	Russia
Akosombo (Lake Volta)	150.0	Ghana
Manicouagan Reservoir	141.9	Canada
Lake Guri	135.0	Venezuela
High Aswan Dam (Lake Nasser)	132.0	Egypt
Bennett W. A. C. (Williston Lake)	74.3	Canada
Krasnoyarsk Reservoir	73.3	Russia
Robert-Bourassa Reservoir	61.7	Canada

Source: ICOLD 2020.

The additional terrestrial water storage created by man-made dams has the effect of partially offsetting losses from other terrestrial water stores (Reager et al. 2016). From 1950 to 2000, which includes the period when global large dam-building activity was at its highest, impoundment equated to an average rate of 184 Bm^3y^{-1} (i.e., a total of 9,200 Bm^3) (Wada et al. 2016). Between 2000 and 2010, the rate of large dam construction slowed to 15 Bm^3y^{-1} (Wisser et al. 2013). Assuming a total 5% loss in storage due to sedimentation (Wisser et al. 2013), the cumulative impact of large dams over the period 1971-2020 is estimated to be a storage increase of 5,500 Bm^3 (i.e., 110 Bm^3y^{-1}). Other man-made water bodies, comprising mainly small reservoirs, are estimated to represent 10% of the total continental water surface area (Ramsar Convention on Wetlands 2018), but in terms of volume, represent only a very small proportion of total global freshwater storage. We estimate that, over the last 50 years, large dam and small dam reservoir storage combined has increased by 7,161 Bm^3 (143 Bm^3y^{-1}). However, due to rising population, siltation and decommissioning of older dams, per capita storage in human-made reservoirs has declined in recent decades.

Wetlands

Wetlands are important stores of water for domestic water supply and agriculture throughout the world, but particularly in dryland areas. Water within wetlands is stored as standing inundation, within soils and within plants, and shallow groundwater. Degradation of wetlands, through direct drainage, infilling or burning (e.g., peatlands), or as a consequence of disrupted hydrological regimes (e.g., downstream of dams and irrigation systems), disrupts storage and releases this water. Furthermore, climate change and anthropogenic modifications to the hydrological cycle are increasing the extent and severity of wetland salinization (Herbert et al. 2015).

Determining the extent of, and water storage in, wetlands is challenging for a number of reasons. First, definitions of a wetland vary. The definition of the Ramsar Convention is very broad and encompasses lakes as well as coastal areas with water, either permanently or seasonally, up to a depth of 6 m (Ramsar Convention on Wetlands 1971). Others define wetlands as land or areas (such as marshes or swamps) that are covered intermittently with shallow water or have soil saturated with moisture. Second, the areal extent of many wetlands varies seasonally, annually and over longer time periods, with many in arid zones only being inundated intermittently. Third, large areas of wetlands are forested, and optical remote sensing approaches fail to distinguish these areas from 'forest'. Over time, different purposes, sources and observation methods have produced a wide range of areal estimates that differ because they use different data sources and relate to different types of wetlands (Davidson et al. 2018). Overall, estimates of wetland extent have increased significantly in recent years because of improving technologies and methods rather than a real increase (Davidson et al. 2018).

Wada et al. (2016) estimated present global inland wetland extent to be 3.71 Mkm^2 and, based on a previous study by Davidson (2014), wetland loss to be 0.565% y^{-1}. Wada et al. (2016) assumed a uniform 1 m depth of water in wetlands (Milly et al. 2010) to estimate the cumulative decline in storage due to wetland drainage as 726 Bm^3 since 1990. The most recent study, utilizing the Ramsar definition of wetlands and encompassing the most up-to-date remote sensing data, estimated a much bigger wetland extent: 12.1 Mkm^2, of which 11.2 Mkm^2 is inland wetlands (Davidson et al. 2018).

Others have produced estimates of wetland loss based on alternative approaches. For example, one study simulated the potential distribution of wetlands based on rainfall and topography and estimated total global wetland loss as 7.2 Mkm^2 (Hu et al. 2017). Another study estimated the global extent of drained organic soils (formed by the accumulation of organic matter under anoxic conditions) for agriculture. This study estimated that 2.6 Mkm^2 had been drained, primarily in boreal and cool temperate and tropical regions (Tubiello et al. 2016). However, neither of these studies were time bound.

The most recent estimate of decline in wetland area is 35% ± 3% (i.e., 3.92 ± 0.18 Mkm^2) in inland wetlands between 1970 and 2015, but with significantly faster rates of loss since 2010. This estimated rate of decline in wetland area was determined by aggregating from analyses of relatively few areas, focused primarily in North America and Europe (Darrah et al. 2019). Extrapolating worldwide almost certainly results in an overestimate of decline in wetland area because observations in relatively unaffected areas (e.g., in Africa, South America and high latitudes) are underrepresented. Nevertheless, applying the rate of wetland loss determined by Darrah et al. (2019) and making the same assumptions as Wada et al. (2016) (i.e., 1 m depth of water) indicates an upper bound of decline in global wetland water storage of 5,010 ± 150 Bm^3 from 1971 to 2020.

Previous studies have made no allowance for increased storage in man-made wetlands, in particular paddy fields, some of which are located on previously natural wetlands. Between 1971 and 2020, the global area of paddy fields increased by 0.3 million km^2 to a total area of 1.671 million km^2 (Davidson et al. 2018). Assuming an average water depth of 0.2 m, this equates to a storage increase of 60 ± 1.8 Bm^3 between 1971 and 2020.

Wetlands have provided water resources and other ecosystem services for human societies for millennia, and some ancient civilizations existed only because of the benefits derived from wetlands. However, degradation over the last 50 years has significantly reduced the total volume of storage; we estimate by approximately 3,314 Bm^3 (i.e., 66 Bm^3y^{-1}). A proportion of this loss has been offset by the construction of man-made wetlands, most notably in Asia, through paddy fields.

Soil Moisture

Soil moisture refers to the water held in soil pores, typically in the upper 2 m of the soil profile. Water storage in the soil profile is essential for plant growth and is, therefore, extremely important for agriculture. Globally, the total volumes of water stored within the soil are small compared to other natural terrestrial stores. Shiklomanov (1993) estimated total global soil moisture storage as 16,500 Bm^3, but more recent estimates have suggested anything up to 122,000 Bm^3, with a median value of 54,100 Bm^3 (Abbott et al. 2019). In contrast to wetlands, soil water stores are generally depleted relatively quickly through evapotranspiration during the growing season but recharged through precipitation and snowmelt. Surface soil moisture (i.e., up to a depth of 0.05 m) is equivalent to only a thin layer (i.e., 8 mm) of water over all continents (1,192 Bm^3) (McColl et al. 2017).

The capacity of soil to regulate the terrestrial freshwater supply is a fundamental ecosystem service. Water percolating through soil is filtered, stored for plant utilization, and partitioned between flows to groundwater, surface water and lateral flows within the soil. Soils, in conjunction with vegetation and topology, play a key role in the rainfall-runoff response of a catchment: splitting rainfall between event-based and longer-term runoff, and evaporation. This, in turn, determines the water yield of a catchment, extent of groundwater recharge, magnitude of natural flow regulation and sediment yield, all of which affect the technical performance of downstream infrastructure (e.g., yield from reservoirs and reliability of irrigation systems) (McCartney et al. 2019). Hence, the sustainability of water resources (both quantity and quality) is directly influenced by soil. Furthermore, the interaction between soil moisture and the lowest layer of the atmosphere plays a critical role in both daily weather and long-term climate regimes (McColl et al. 2017). Consequently, though only a relatively minor component of the global water budget, soil water storage plays a disproportionately significant role in the global water cycle and is hugely important for ecosystems and human well-being.

Soil erosion is broadly defined as the accelerated removal of topsoil from the land surface through water and wind. Deforestation, overgrazing, tillage and unsuitable agricultural practices are among the primary causes for enhancing soil erosion. Soil erosion can affect the infiltration, storage and drainage of water from soil. The Global Soil Partnership, led by the Food and Agriculture Organization of the United Nations (FAO), reported that 75 billion tonnes of soil are eroded every year from arable lands worldwide (GSP 2016). A more recent study investigated global soil erosion dynamics by means of high-resolution spatially distributed modeling and concluded that 35.9 billion tonnes of soil were eroded in 2012, of which 17 billion tonnes was from croplands (Borrelli et al. 2017). As well as adversely affecting soil fertility and emitting large amounts of carbon into the atmosphere, erosion of soils not only reduces storage in downstream reservoirs because of sedimentation (see section *Reservoirs* above) but also reduces soil moisture storage.

There have been a few studies of soil moisture trends at global scales, and those that have been conducted have resulted in divergent conclusions due to different data and study periods. Using data from a land surface model, one study found that global soil moisture experienced a wetting trend from 1950 to 2000 (Sheffield and Wood 2008). Another study using satellite data concluded that there had been a reduction between 1988 and 2010 (Albergel et al. 2013). The most recent study, utilizing data from a range of sources, concluded that on average surface soils (top 0.10 m) from non-ice covered land have been drying since at least 1979. Regional differences exist, but the area where soil moisture was decreasing accounts for 68% of the Earth's non-ice covered land area. Decreasing soil moisture was particularly prevalent in eastern China, Mongolia, southern Russia, East European Plain, north-central Africa, USA, and eastern Brazil. Globally, the rate of drying was estimated to be -0.046×10^{-3} m^3y^{-1} per cubic meter of soil for the period from 1979 to 2000 and -0.126×10^{-3} m^3y^{-1} per cubic meter of soil for the period from 2001 to 2017 (Deng et al. 2020). Extrapolating this rate of loss to the top 2 m of the soil equates to 135 Bm^3 and 268 Bm^3 of water lost from soil storage for the periods 1979–2000 and 2001–2017, respectively. Deng et al. (2020) attributed 65.1% of the drying to rising temperatures and hence enhanced evapotranspiration.

Under drying conditions, the depth to the point of water exchange between soil and atmosphere increases, and the regulating capacity of soil reservoirs is weakened. In addition, soil organic carbon is mineralized (Achat et al. 2012), thereby increasing the loss of organic carbon, and soil microbial respiration rates decrease (Manzoni et al. 2014). Poor soil conditions can lead to the degradation of soil and water quality, and ecosystems. Soil drying can result in more frequent agricultural droughts and food security problems and, by modifying the near surface energy budget, contribute to heat waves and high temperatures across large areas (Deng et al. 2020).

Although only a very small fraction (0.13%) of the world's stored freshwater, soil moisture is a key component of the terrestrial water budget and, not least through its critical role in agriculture, vital for human well-being. Based on past studies, we estimate that soil loss and degradation has resulted in a decrease of 519 Bm^3 (i.e., 10.4 Bm^3y^{-1}) in soil water globally over the last 50 years.

Aggregate Freshwater Storage and Cumulative Change

Aggregate Freshwater Storage

Based on the literature reviewed above, total water storage in ice caps, glaciers and other terrestrial water stores is estimated to be 52,667,432 Bm^3, of which 42,169,008 Bm^3 is freshwater. Of total water storage, 99.5% is in ice and groundwater (Figure 1). Other storage, including lakes, soil moisture, large and small dam reservoirs, wetlands and paddy fields, collectively make up less than 0.5% of total water storage.

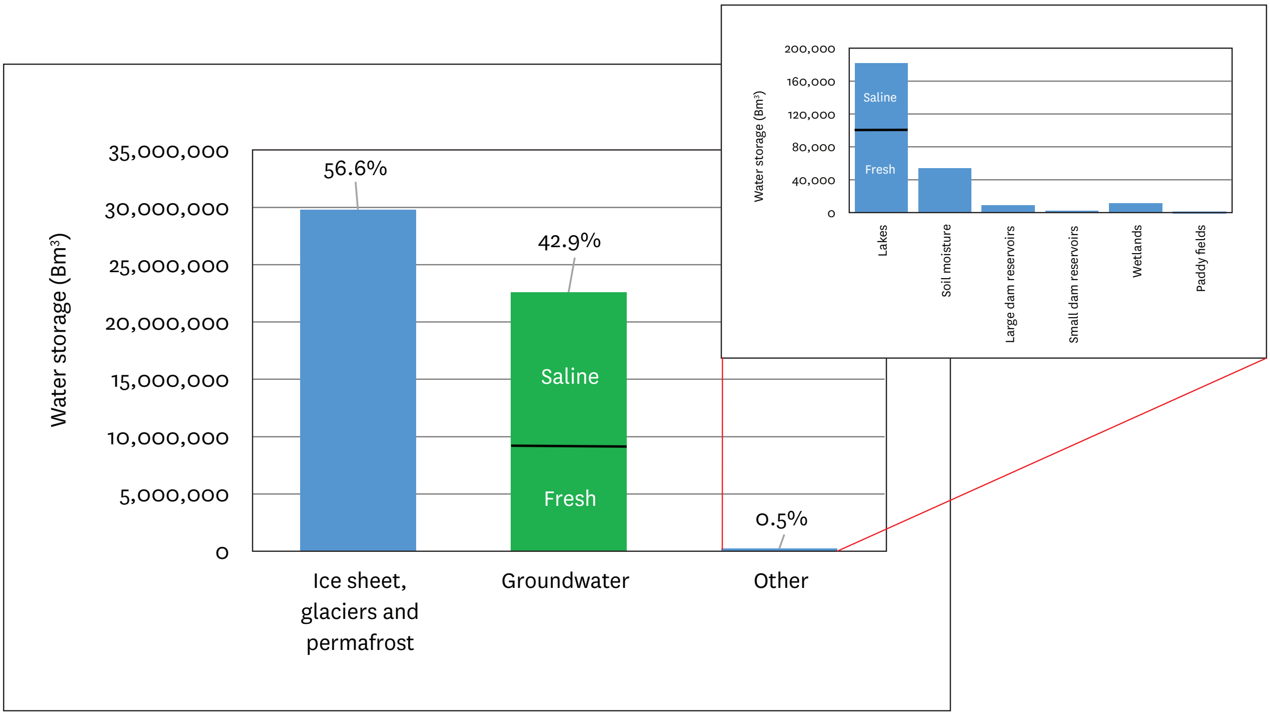

Figure 1. Global distribution of total terrestrial water storage.
Data sources: see section *Water Storage*.

From a human water security perspective, not all forms of water storage are equal. A range of biophysical and socioeconomic factors determine whether water can be withdrawn from storage to contribute to human endeavors. We define water storage from which water can be withdrawn sustainably for direct human use as 'operational' water storage.[3] Of course, much of the water stored – in all forms of storage – supports ecological processes that underpin ecosystem services that contribute to human well-being. This water cannot be sustainably extracted and this storage is not operational storage.

Table 4 disaggregates total water storage in steps to arrive at an estimate of global operational freshwater storage – approximately 850,000 Bm^3. Given the nature of the underlying data, such estimates are necessarily approximate but are valuable insofar as they start to illustrate the relative scale of the forms of freshwater storage that are most relevant to human water security. As indicated in Figure 2, only 2% of total global terrestrial water storage is operationally relevant. This is almost certainly an overestimate because only a proportion of freshwater in lakes, soils and wetlands is usable in a sustainable manner. Despite only 5% of groundwater being included in the estimate, it still makes up over 60% of operational freshwater storage. Other major categories include mountain glaciers, lakes and soil moisture (see Figure 2). Man-made storage contributes to less than 1.5% of operational storage (Figure 2).

[3] Operational water storage is the proportion of water in the store that can be sustainably extracted for direct human utilization.

Table 4. Aggregate estimates of global freshwater storage.

	A	B	C	D	E
Water stores	Total water storage (Bm³)	Total freshwater storage (Bm³)	Freshwater storage without ice sheets (Bm³)	'Operational' freshwater storage (Bm³)	'Operational' freshwater storage (%)
Antarctic ice sheet	26,500,000	26,500,000			
Greenland ice sheet	2,850,000	2,850,000			
Mountain glaciers	158,000	158,000	158,000	158,000	18.4%
Permafrost (ground ice)	300,000	300,000	300,000		
Groundwater	22,600,000	10,396,000	10,396,000	519,800	60.7%
Lakes	182,900	102,424	102,424	102,424	12.0%
Soil moisture	54,100	54,100	54,100	54,100	6.3%
Large dam reservoirs	9,025	9,025	9,025	9,025	1.1%
Small dam reservoirs	1,873	1,873	1,873	1,873	0.2%
Wetlands (marshes, peatlands and swamps)	11,200	11,200	11,200	11,200	1.3%
Paddy fields	334	334	334	334	0.04%
Total	52,667,432	40,382,956	11,032,956	856,756	100%

Notes: Explanation of details in columns A to E:

A – includes all water storage based on the best available estimates as described in the section *Water Storage*. Table 5 includes the references for each estimate.

B – excludes saltwater based on percentage estimates for groundwater and lakes (Figure 1).

C – excludes water storage in the Antarctic and Greenland ice sheets as their location makes them generally unavailable for large-scale human use.

D – an attempt to estimate which parts of freshwater storage are 'operationally' relevant to current human water security. It excludes permafrost on the basis that it is currently not available for human use, and includes only the 5% of groundwater that is considered 'renewable and readily available'.

E – the percentage of operationally relevant storage as defined in column D.

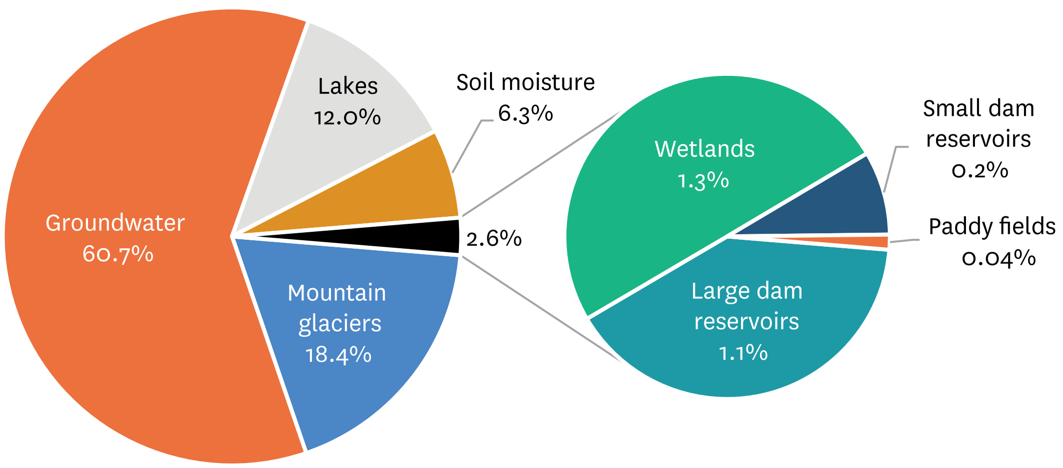

Figure 2. Operational freshwater storage.

Note: see Table 4 for derivation of operational freshwater storage.

Cumulative Change in Water Storage

Table 5 presents an estimate of changes in terrestrial water storage over the 50-year period 1971-2020. The total change over 50 years is estimated to be a reduction of storage of 27,079 Bm^3 with a net contribution of 15,268 Bm^3 from terrestrial water sources, including glaciers but excluding ice caps. Figure 3 presents the changes in total water stored for the period 1971-2020. The loss of 27,079 Bm^3 of storage includes a reduction of 33,944 Bm^3 in natural storage, which is partially offset by an increase of 6,865 Bm^3 in built storage (reservoirs) and paddy fields over the same period.

Human interventions have contributed both positively and negatively to terrestrial water storage. The filling of man-made surface water reservoirs (behind small and large dams) as well as, to a very small extent, the creation of paddy fields are estimated to have added storage from the 1970s. Other interventions have predominantly resulted in declining volumes of water in terrestrial stores. Groundwater depletion, degradation of wetlands, depletion of lakes and soil degradation are estimated to have resulted in a decline in terrestrial water storage from the 1970s.

Table 5. Estimated global water storage and change over the period 1971-2020.

Water stores	Current storage (Bm^3)*	Change in storage (Bm^3)	Data sources
Antarctic ice sheet	26,500,000	-6,435	Total storage: WCRP 2018 Rate of change: Rignot et al. 2019
Greenland ice sheet	2,850,000	-5,377	Total storage: WCRP 2018 Rate of change: Mouginot et al. 2019
Mountain glaciers	158,000	-8,666	Total storage: Farinotti et al. 2019a Rate of change: WCRP 2018
Permafrost (ground ice)	300,000	-	Total storage: Shiklomanov and Rodda 2003
Groundwater	22,600,000 (10,396,000)	-7,041	Total storage: Gleeson et al. 2012 Rate of change: de Graaf et al. 2017
Lakes	182,900 (102,424)	-1,986	Total storage: Messager et al. 2016 Rate of change: WCRP 2018
Soil moisture	54,100	-519	Total storage: Abbott et al. 2019 Rate of change: Deng et al. 2020
Large dam reservoirs	9,025	5,778	Total storage: GRanD database version 3; ICOLD 2020 Rate of change: WCRP 2018; Wisser et al 2013.
Small dam reservoirs	1,873	937	Total storage: Lehner et al. 2011 Rate of change: WCRP 2018; Wisser et al. 2010
Wetlands (i.e., peatlands, marshes and swamps)	11,200	-3,920	Total storage based on wetland extent: Davidson et al. 2018; Wada et al. 2016 Rate of change of wetland extent: Darrah et al. 2019
Paddy fields	334	150	Total storage and rate of change based on paddy extent: Davidson et al. 2018; this study
Total	52,667,432 (40,382,956)	-27,079	

Note: * Number in brackets = freshwater.

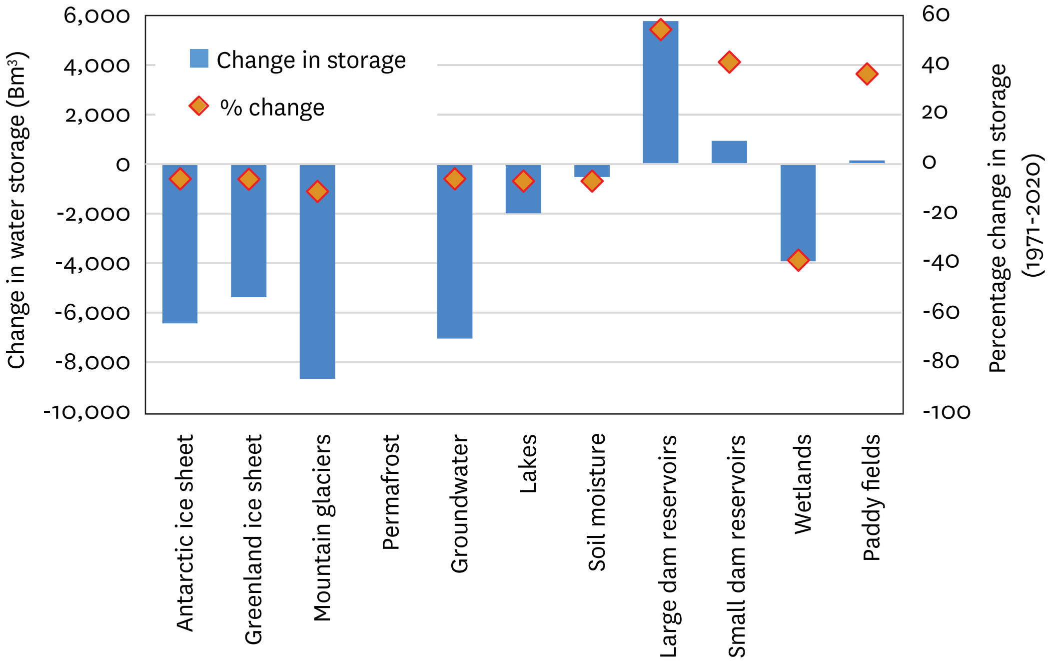

Figure 3. Estimate of changes in water storage for the period 1971-2020.

Every year, land temporarily stores and then releases approximately 6,000 ± 1,400 Bm^3 of water through seasonal cycling (Reager et al. 2016). Climate-driven variability in rainfall, evaporation and runoff also contributes to decadal rates of change by adding or subtracting water from the various stores. Until recently, climate-driven changes in land water storage were assumed to be negligible. However, these changes are incorporated in GRACE estimates, and according to Reager et al. (2016), they exceeded the changes associated with direct human modification of water stored in recent years. They estimate that between April 2002 and November 2014, these climatic changes equated to a total gain in terrestrial water storage of 36,919 ± 10,400 Bm^3 over 12 years with a pattern of mid-latitude drying – which is more pronounced in the northern hemisphere – and of high- and low-latitude wetting (Reager et al. 2016). These results partially contradict the more recent findings of Deng et al. (2020) that near surface soils are drying on average, largely as a consequence of increasing evapotranspiration (see section *Soil Moisture*). Nevertheless, they highlight the fact that climate-driven changes in terrestrial water stores, in part reflecting climate change, are of the same order of magnitude and likely still exceed direct anthropogenic changes.

There remains great uncertainty but, overall, the results confirm that direct human-induced change since 1971 is an insignificant proportion (just 0.25%) of total water stored in non-ice cap terrestrial water stores. However, this is misleading because as a proportion of the estimated operational freshwater storage (and much of the change is in the operational portions), it is much more significant. Very conservatively, we estimate that there has been a decline greater than 3%, and more realistically, it could be a decline greater than 5%, in operational water storage at the global scale. This has a considerable impact at local and regional scales.

Climate-driven changes, increasingly incorporating a component of anthropogenic forcing, remain greater than direct human impacts. Nevertheless, changing water storage adds to the multiple stressors on water availability at regional and local scales. For people and communities, global changes – except insofar as they impact sea level rise – are largely irrelevant. Rather, what matters for societies are the changes in storage that impact the availability of water in the areas in which they live or where agricultural (food, feed, fiber and fuel) and/or hydropower production takes place. In highly populated river basins where reserves in both natural and man-made stores are declining simultaneously, water resources management is increasingly constrained. At the same time, with increases in population and economic development driving greater water demand and hence storage needs in many locations, the widening storage gap has serious implications for system resilience, water-related risks, and long-term sustainable development (Abbott et al. 2019; Yu et al. 2021).

Future Trends

Although there remains considerable uncertainty in future projections, current computer simulations suggest that accelerating climate change will further reduce terrestrial water storage (Pokhrel et al. 2021). The recent Sixth Assessment Report (AR6) of IPCC (IPCC 2021) indicated the following:

- Glaciers are likely to continue to lose mass under all emissions scenarios, with maximum rates of glacier mass loss in low latitude (mountain) regions taking place in the next few decades.

- Groundwater recharge will likely increase in places where precipitation intensities are expected to rise. However, in many environments, such climate-related impacts are expected to occur in the context of (continued) substantial human withdrawals depleting groundwater storage. Sea level rise is also likely to increase saltwater intrusion into coastal aquifers. Current global climate models are thought to underestimate rainfall intensities and are hence likely underestimating future groundwater recharge. Therefore, it is not possible to determine the likely overall impact on groundwater storage (Cuthbert et al. 2019a, 2019b).

- There will be a reduction in inland wetland extent in regions where precipitation is projected to decrease and evaporation to increase. Also, sea level rise will increase saltwater intrusion into coastal wetlands, suggesting that freshwater storage in wetlands will decline further even if direct human-induced degradation ceases.

For lakes, there is limited evidence to assess future changes, but it can be speculated that as with wetlands, freshwater storage will decline where rainfall and runoff decrease and in locations where human abstractions divert significant volumes of inflowing water. In areas with more direct runoff (due to intensive rainfall as a result of climate change and land degradation), more sedimentation will lead to an accelerated decline in lake water storage. Salinity will tend to increase in places where evaporation increases.

Large and small dam building will likely continue into the future, perhaps even increasing over current rates of construction if they are seen as being critical for climate change adaptation, although the primary purposes of such dams may evolve along with climate change and human needs. Even with significant increases in other renewable energy sources (solar and wind), both the International Energy Agency and the International Renewable Energy Agency foresee a need for a significant increase in hydropower capacity to contribute to the increasing demand for electricity (particularly in emerging markets and developing economies) and for climate change mitigation (IEA 2021; IRENA 2021). There remains significant potential for further hydropower development in countries in Africa and Asia where hydropower is less developed (IHA 2021). Increasing irrigation as a measure to adapt to climate change by reducing risks of crop failure may also to lead to investment in the construction of both large and small reservoirs. However, there may be a decline in water storage in reservoirs in places where flows reduce as a consequence of a decrease in precipitation and increase in evaporation. Globally, reservoir storage, behind both large and small dams, will also continue to decline in places as a consequence of sedimentation and as current infrastructure continues to age and is increasingly decommissioned.

Conclusions

Water storage is a critical element of water, food, and energy security. Human societies have modified global water stores, directly and indirectly, for thousands of years. Until recently, such changes were insignificant in comparison to changes arising from climate variability. In the age of the Anthropocene, human-induced changes in terrestrial water storage, arising as a consequence of the dual impacts of climate change and direct human activities, while still relatively small at the global level, have become more significant and are now approximately the same order of magnitude as those arising from natural climate variability. Although much uncertainty remains, melting ice, groundwater depletion and degradation of wetlands are the dominant causes of change in storage, exhibiting large changes in volumes of water stored in recent decades.

This review has underscored the extent of long-term cumulative loss from a wide range of natural water stores, as a consequence of human-induced changes. These losses have been partly offset by the proliferation of large and small dams and are minor in comparison to total land water storage, but are much more significant in relation to operational freshwater storage. Also, with the exception of ice melt, losses have most likely occurred disproportionately in areas where human populations are highest and water storage is most important for well-being. Decades of degradation of lakes, wetlands and soil, and diminishing storage volumes in reservoirs, as well as groundwater depletion complicate future water resources management, reduce adaptive capacity, and ultimately undermine the resilience of societies that are increasingly under threat from the impacts of climate change.

Data presented in this review strongly suggest that, despite large amounts of human investment in built infrastructure over the last 50 years, these cumulative efforts have not come close to replacing the water losses in natural storage caused by human behavior. This suggests that more integrated approaches to terrestrial freshwater storage (i.e., much greater use of natural landscapes/stores as an integral part of the full spectrum of storage available to contribute to societal needs/demands) will be critical to human progress in the future.

The contribution of both man-made and natural water stores to human well-being cannot be overstated. Ecological regimes and functions and hence ecosystem services, both aquatic and terrestrial, also depend on adequate water storage. The demands of growing populations with rapidly changing consumption patterns for food, mobility and energy are exerting ever-increasing pressure on water resources. Additionally, the future is likely to see greater frequency and severity of extreme weather events as a result of climate change. In conjunction with the legacy of past perturbations, this will likely increase the stress on water resources. Water use and management practices must adapt to changing circumstances. In the future, water storage will be increasingly important and more efforts are needed to protect existing storage. It is vital that natural water stores are fully integrated, alongside man-made water infrastructure, in water resources planning and management. Conjunctive use of different water stores is a prerequisite for future water security.

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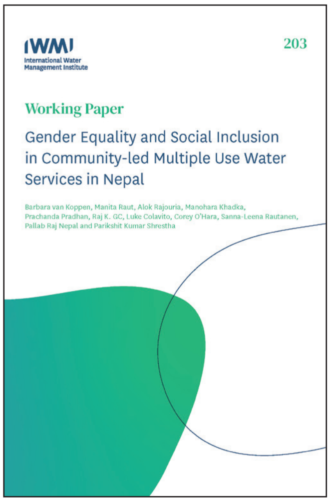

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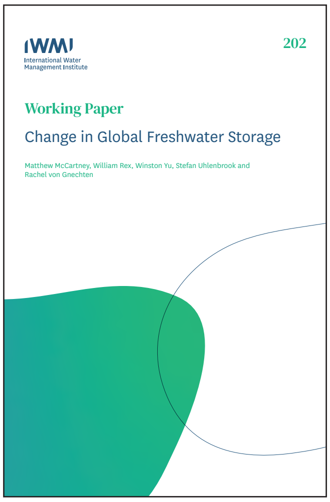

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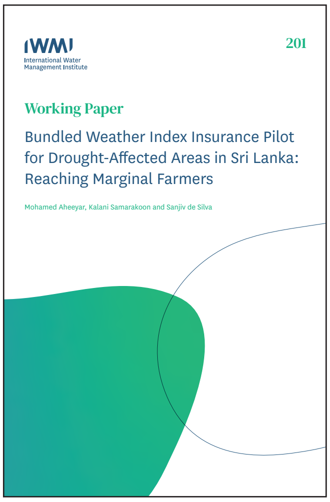

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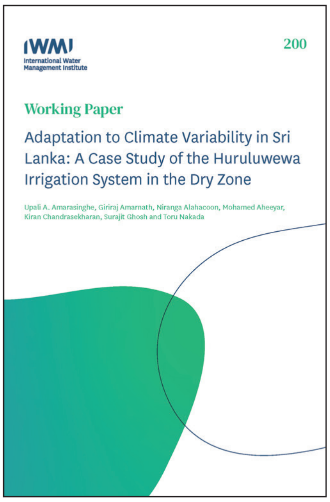

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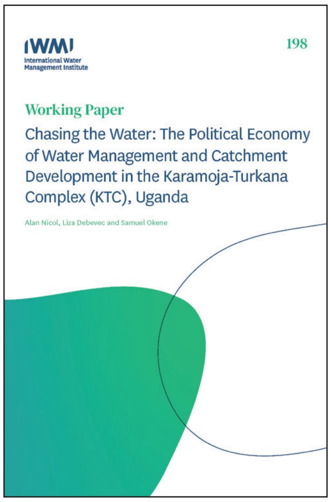

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