CHAPTER 1

Trends in and Causes of Global Freshwater Decline

Key findings

- Global freshwater reserves, including the total amount of water stored above ground and in aquifers, have declined at an annual rate of 324 billion m^3—enough to meet the annual water needs of 280 million people—over the past two decades. The median basin-level reduction in freshwater is equivalent to about 3 percent of the annual renewable freshwater supply across all basins and 10 percent in arid basins already expericing drying.
- Although most of the world's dry areas continue to get drier and its wet areas continue to get wetter, dry areas are drying at a faster rate than wet areas are wetting, creating continental-scale mega-drying regions.
- Global warming, worsening droughts, and unsustainable water and land use all contribute to the reduction in global freshwater reserves.

Introduction

The year 2024 was the hottest year on Earth since records began in 1850 (NOAA 2025). Relentless heat waves scorched continents, and global temperatures surged to unprecedented levels, turning what was once extreme into the new normal. However, the consequences of rising temperatures extend beyond increased heat. As temperatures increase, evaporation from the Earth's surface accelerates, increasing the amount of water vapor in the atmosphere and disrupting the global water cycle. According to the Intergovernmental Panel on Climate Change, each additional increment of global warming intensifies water-related weather extremes, leading to more severe floods and prolonged droughts (Core Writing Team, Lee, and Romero 2023).

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A changing water cycle directly affects the availability of freshwater, as seen in shifts in freshwater reserves or terrestrial water storage (TWS). TWS is the total amount of water stored on land, including water found in glaciers, rivers, lakes, reservoirs, and aquifers and water held in soil moisture and vegetation. This chapter examines long-term TWS changes to assess the trends in freshwater availability, using more than two decades of data from the Gravity Recovery and Climate Experiment (GRACE) missions of the U.S. National Aeronautics and Space Administration (NASA) and the German Aerospace Center.

Numerous studies have identified TWS changes based on GRACE data (Reager et al. 2016; Rodell and Li 2023; Rodell et al. 2018, 2024; Scanlon et al. 2022). Burke et al. (2023) highlighted the long-term cumulative loss in TWS reported in various literature, and GCEW (2024) underscored the decline in TWS from 2002 to 2016.

Although regional trends are relatively well characterized in existing studies, uncertainties remain regarding whether these trends are robust, what the underlying drivers are, and whether the global continents, as a whole, are gaining or losing freshwater from or to oceans (Kim et al. 2019). Additionally, most studies are conducted at lower-resolution grid cells of $3^\circ \times 3^\circ$, meaning Earth's surface is divided into squares approximately 330 km by 330 km at the equator, akin to the size of a small country. Although this grid captures broad patterns, it limits detection of finer-scale changes, such as those occurring in smaller watersheds or local aquifers.

This chapter provides a comprehensive assessment of TWS changes over the past two decades, building and improving on the findings of previous studies. It presents the latest long-term trends in TWS from April 2002 to April 2024 on both global and regional scales. Additionally, the resolution of satellite observations has been enhanced from $3^\circ \times 3^\circ$ to $0.25^\circ \times 0.25^\circ$ (approximately 25 km by 25 km at the equator), allowing for more precise characterization of TWS changes at administrative boundaries, such as countries, states, and even counties. This finer resolution is integrated with socioeconomic data to uncover the drivers of TWS changes using novel methods.

Findings from the analysis reveal that the global continents (all land excluding Antarctica and Greenland) have undergone unprecedented rates of TWS loss since 2002—a phenomenon termed *continental drying* in this report. Although most of the world's dry areas continue to get drier and its wet areas continue to get wetter, dry areas are drying at a faster rate than wet areas are wetting. The rapid expansion of dry areas has led to the formation of mega-drying regions by connecting previously identified drying hot spots.

Using global hydrological models and econometric analyses, this chapter provides empirical evidence that human water and land use activities have significantly influenced changes in global freshwater reserves. Unregulated and poorly managed extraction of surface water and groundwater, combined with deforestation and wetland degradation, has intensified water scarcity. Although the crisis of our warming planet is fundamentally a water crisis, ineffective water management has exacerbated it.

Continental drying as seen from space

Monitoring changes in the availability of freshwater is critical for water resources management. However, tracking how water moves and is stored on Earth has been notoriously difficult, especially for groundwater, which represents 97 percent of Earth's unfrozen freshwater. In 2002, NASA and the German Aerospace Center launched a satellite mission, GRACE, which operated from 2002 to 2017, followed by its successor mission, the GRACE Follow-On (GRACE-FO), launched in 2018. By monitoring small but continuous changes in Earth's gravity field driven by the movement of water, GRACE and GRACE-FO (hereafter, GRACE) have allowed the measurement of how freshwater reserves vary in space and time across the entire planet (refer to box 1.1).

BOX 1.1

A scale in the sky: Measuring change in Earth's freshwater resources

The Gravity Recovery and Climate Experiment (GRACE, 2002–17) and its successor, the GRACE Follow-On (GRACE-FO, 2018–present) missions use two satellites that orbit the Earth and measure the distance between them with high precision, down to micrometers (a micrometer is 1/50th the width of a human hair). As the pair of satellites circle Earth, their positions are changed slightly by the amount of water mass in the region below. For example, when the front satellite approaches a large water reservoir, it accelerates because it is pulled slightly by the reservoir's gravity, changing the distance between the two satellites. When it has passed over the reservoir, it decelerates, and the velocity of the second satellite increases, again changing the distance between the two satellites. The next month, if the reservoir has lost water, the overall pull by the reservoir will be smaller; thus, the satellites' acceleration and deceleration will be smaller. The difference between the two months' measurements is then

(continued)

BOX 1.1

A scale in the sky: Measuring change in Earth's freshwater resources *(continued)*

converted into water mass units, after accounting for the other influences. By monitoring these small but continuous changes in Earth's gravity field, GRACE functions like a scale in the sky, enabling researchers to observe fluctuations in terrestrial water storage (TWS).

Although GRACE data are powerful, they have some limitations. First, although the satellite observations provide valuable large-scale measurements of TWS, their inherent resolution can be too coarse for practical regional water management applications. Thus, the regional analysis in this report uses higher-resolution (0.25° × 0.25°) estimates of TWS from the GRACE-assimilated National Aeronautics and Space Administration Global Land Data Assimilation System Version 2 model after additional bias correction (refer to the online technical appendixes).[a] Second, although GRACE offers the only direct observational data on total freshwater reserves, its relatively short observation period limits assessment of longer-term trends. However, recent studies incorporating extended data sets have identified declines in various components of TWS over longer time periods—including the long-term depletion of soil moisture (Seo et al. 2025), groundwater (Wada et al. 2010), surface water (Pekel et al. 2016), and lake storage (Yao et al. 2023)—reinforcing the findings of this study. Third, the GRACE missions observe monthly changes in TWS—not the absolute amount of TWS. Understanding the absolute amount of freshwater on and below the land surface would require an unprecedented level of exploration of Earth's shallow crustal water environment.

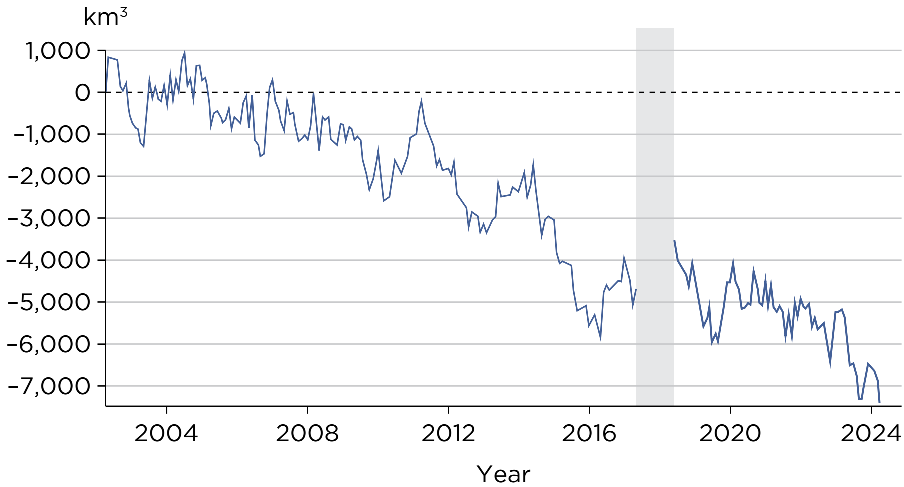
a. The technical appendixes are available online at https://hdl.handle.net/10986/43683.

Global land is losing freshwater to oceans

Globally, a key finding from the analyses of GRACE data is the consistent net loss of freshwater reserves at an annual rate of 324 billion m^3—enough to meet the annual water needs of 280 million people—over the past two decades (refer to figure 1.1). A long-term deficit in freshwater reserves indicates that water losses from land consistently exceed gains from precipitation, leading to a continuous depletion of freshwater reserves. If this trend continues, it will render the system unsustainable. The water lost from land ultimately flows into oceans, contributing to mass-driven sea level rise. For more details of the analysis, refer to Chandanpurkar et al. (2025).

Global freshwater availability has persistently declined over the past two decades.

FIGURE 1.1 Global freshwater loss to oceans, 2002–24



Source: Adapted from Chandanpurkar et al. 2025.
Note: This figure depicts the long-term loss of the global land water mass, measured by the net change in globally integrated, deseasoned TWS data from April 2002 to April 2024. TWS data are from the National Aeronautic and Space Administration's GRACE satellite mission, which operated from 2002 to 2017, and its successor mission, GRACE-FO, launched in 2018. The gray band indicates the gap period between the GRACE and GRACE-FO missions. GRACE = Gravity Recovery and Climate Experiment; GRACE-FO = Gravity Recovery and Climate Experiment Follow-On; km^3 = cubic kilometers; TWS = terrestrial water storage.

The emergence of continental-scale mega-drying regions

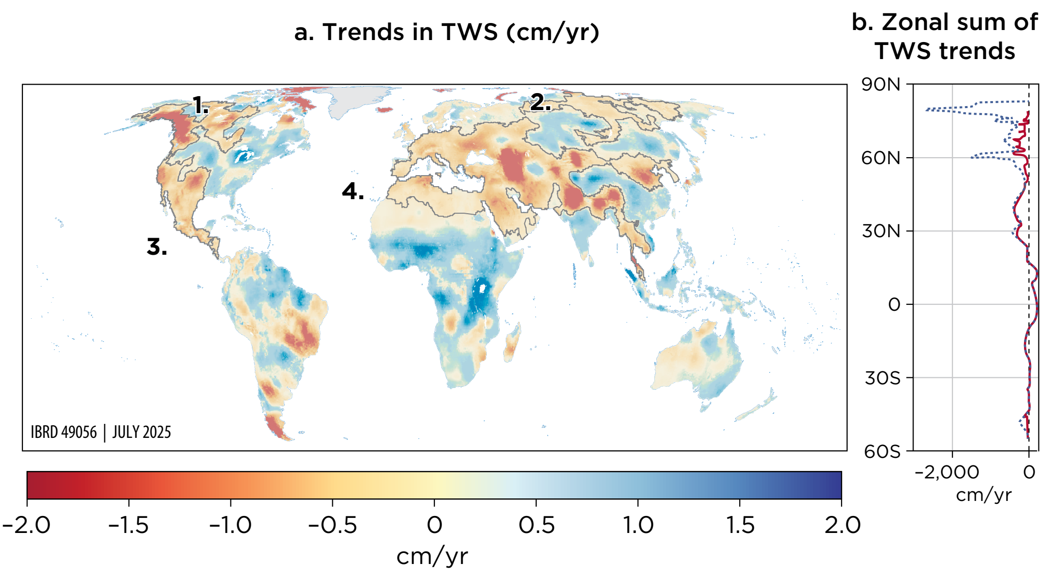
Beyond the global average, the trend varies across regions. Analyzing TWS trends at each land location reveals several hot spots of pronounced freshwater decline (refer to map 1.1). Some of these hot spots are well documented (for example, Rodell et al. 2018), including glaciers in Alaska, Canada, Central Asia, Patagonia, and the Himalayas, and the nonglaciated regions in northern China, northern India, the Middle East, and the southwestern United States. In recent years, however, the decline in TWS has also been seen in Central America, most of Europe, and high-latitude but nonglaciated parts of Eurasia and North America.

A major finding of this report is that the land between the previously identified hot spots is also consistently losing TWS, forming what is described in this report as continental-scale mega-drying regions, as illustrated in map 1.1a. These regions include (1) Alaska and western and northern Canada, (2) northern Russian Federation, (3) Central America and southwestern North America, and (4) the vast three-continent landmass that includes Europe, the Middle East and North Africa, Central Asia, South Asia (except peninsular India), Southeast Asia, and northern China.

The large-scale continental drying is also evident in the zonal plot in map 1.1b, which shows that all latitudes, except for the tropics between 10°S and 20°N, exhibit negative TWS trends, with or without accounting for the presence of glaciers. The trends have persisted for the past 22 years, showing little sensitivity to a lengthening GRACE record.

Rapid expansion of dry areas has led to the emergence of continental-scale mega-drying regions.

MAP 1.1 Emergence of continental-scale mega-drying regions



Source: Chandanpurkar et al. 2025.
Note: In panel a, red indicates regions that have experienced a persistent loss of freshwater reserves over the past two decades, and blue indicates areas that have consistently gained freshwater reserves during the same period. Intensity of color corresponds to the magnitude of water loss or gain. The numbers on the map indicate the mega-drying regions: 1 = Alaska and western and northern Canada; 2 = northern Russian Federation; 3 = Central America and southwestern North America; (4) Central Asia, northern China, Europe, the Middle East and North Africa, South Asia (except Peninsular India), and Southeast Asia. The zonal plot in panel b shows the sum of TWS across parallel lines, for all regions (blue dotted line) and for nonglaciated regions (red). It shows that, with the exception of the tropics between 10S and 20N, all latitudes exhibit a net decline in freshwater reserves, even when excluding glaciers and ice caps. cm/yr = centimeters per year; TWS = terrestrial water storage.

This persistent drying is accompanied by increased area under dry TWS anomalies and extremes. The locations experiencing below-average monthly TWS have been increasing by an average of 831,600±69,100 km^2 per year—more than the size of the Amazon River Basin.[1] The regions facing dry extremes—defined as below-average monthly TWS values that exceed 1 local standard deviation—has also grown at a similar rate, by an average of 845,000 ± 122,600 km^2 per year. This trend is primarily driven by drying in nonglaciated regions, which make up 72 percent of the area under dry anomalies and 81 percent of the area experiencing dry extremes. In contrast, both the areas becoming wetter and the regions experiencing wet extremes have decreased over the past 22 years (refer to box 1.2).

BOX 1.2

Drenched yet dry: Wetting and economic water scarcity

Although the continents are, on average, losing water, there are both wetting and drying hot spots—places that have experienced persistent increasing and decreasing amounts, respectively, of terrestrial water storage (TWS). Notably, wetting trends have been observed in eastern Australia, eastern central China, the northern Great Plains, northern North America, and the Okavango Delta in Southern Africa. These wetting trends were identified in Rodell et al. (2018) but have grown weaker. There are also wetting regions in which the magnitude of the latest trends is more pronounced than in the study period in Rodell et al. (2018). These regions include humid regions in central Africa, the Amazon, central India, Indonesia, and eastern North America.

Sub-Saharan Africa is the only region that shows an overwhelming increase in TWS (Rodell and Li 2023; Scanlon et al. 2022). This increase is largely due to a pronounced recent increase in precipitation in eastern and northern Sub-Saharan Africa that is likely due to natural climate variability patterns such as the El Niño–Southern Oscillation and the Indian Ocean Dipole, which caused widespread flooding and affected more than 2.8 million people (Wainwright et al. 2021). Because these natural climate variability patterns are tightly linked to the regional ocean temperature, their frequency and intensity are likely to increase with continued warming of oceans. This extreme wetting somewhat masked declining TWS because of groundwater and surface water consumption in the region.

(continued)

BOX 1.2

Drenched yet dry: Wetting and economic water scarcity *(continued)*

Although many parts of Sub-Saharan Africa do not face physical water scarcity, economic water scarcity remains a significant challenge because of inadequate infrastructure. Consequently, only 32 percent of the region's population has access to safely managed drinking water—that is, drinking water that is accessible on the premises, available when needed, and free from contamination. The situation is even more severe in rural areas, where access dropped to just 16 percent in 2022.

Inadequate water storage exacerbates seasonal water scarcity, a form of economic water scarcity. For instance, Cherrapunji, India, receives high annual rainfall, exceeding 11,000 mm, making it one of the wettest places on Earth. However, the vast majority of this rainfall occurs during the monsoon season (June to September). Because it has insufficient infrastructure for capturing and storing water, the city struggles to balance water supply and demand between wet and dry seasons, often facing severe shortages outside the monsoon months.

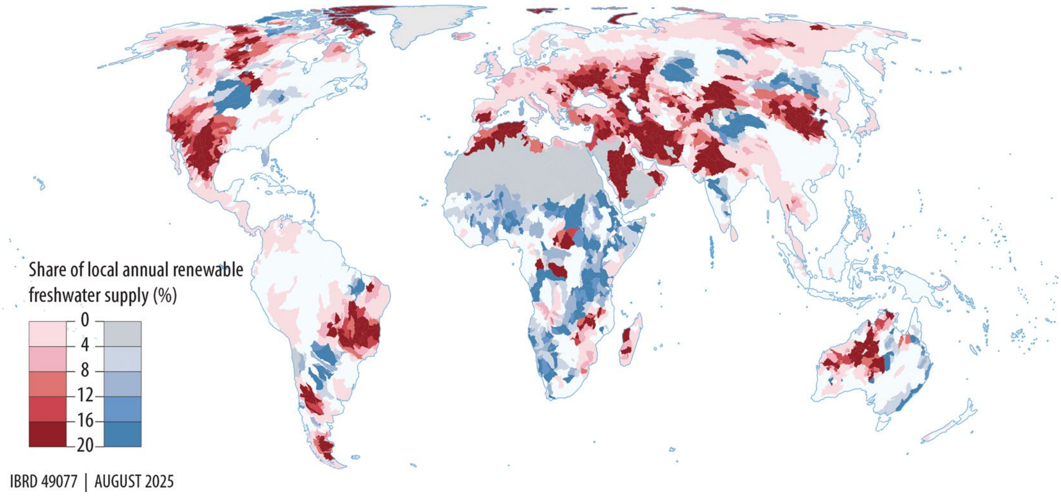
Relative importance of the drying trend

How significant are these TWS trends at the local level? To answer this question, the analysis for this report aggregates TWS trends across 4,639 river basins around the world and compares them with the annual renewable water supply in each basin, using enhanced-resolution GRACE data. The renewable water supply represents the remaining precipitation after accounting for evapotranspiration losses and the environmental flows necessary to sustain ecosystem health and the natural water cycle. Map 1.2 illustrates the magnitude of TWS trends as a share of the annual renewable water supply.

Globally, the median long-term TWS trend magnitude is about 3 percent of annual freshwater supply of all basins, 5 percent of the basins that are drying, and 2 percent of the basins that are wetting. The median TWS trend is 8 percent of annual renewable water supply for arid basins and 10 percent for basins that are arid and experiencing drying. The latter include basins in the southern midlatitudes in Australia, South Africa, and South America; in the Middle East and North Africa; and in the southwestern United States.

Continental drying exacerbates water scarcity in areas that can least afford it.

MAP 1.2 **The median long-term TWS trend as a share of annual renewable freshwater supply, 2003–24**



Source: Chandanpurkar et al. 2025.
Note: Red indicates drying regions, and blue indicates wetting regions. The analysis ignores hyperarid desert regions (aridity index < 0.03), where TWS is low.
TWS = terrestrial water storage.

Notably, TWS values represent long-term trends, whereas water supply values are annual. A river basin's TWS trend would not be negative if its renewable water supply consistently exceeded water demand and losses. The basins highlighted in red on map 1.2 indicate regions where water losses and demands have persistently outpaced renewable supply, making it increasingly difficult to offset water storage deficits.

Drivers of continental drying

What causes the decline in freshwater reserves? Findings from previous studies and analysis for this report indicate that the global trend of decreasing TWS can predominantly be attributed to global warming, the increasing severity and duration of droughts, and human activities related to water consumption and land use change.

Snow and glacier melting substantially affect TWS in the context of global warming (Immerzeel et al. 2020). Moreover, studies have shown the significant impacts of droughts on TWS (Anyah et al. 2018; Castle et al. 2014;

Famiglietti et al. 2011; Liu et al. 2022). During a drought, rainfall deficits decrease runoff, soil moisture, and groundwater recharge, and rising temperatures increase atmospheric evaporative demand, leading to the loss of water from the soil. The severity of droughts has worsened in the past five years (Büntgen et al. 2021; NOAA 2025; Rodell et al. 2024; Rodell and Li 2023).

Additionally, earlier studies highlighted the complex interactions between human activity and climate change. For example, during periods of drought, when water resources become scarce, the interplay between climatic factors and human activities can accelerate the use of groundwater and surface water, leading to reductions in groundwater and lake water storage (Famiglietti et al. 2011; Wada et al. 2010; Yao et al. 2023).

Human activities, independent of reaction to droughts, also play a significant role in the depletion of freshwater resources through excessive water withdrawal and changes in land use. Groundwater, which provides on-demand local access to water, serves as a prime example of a common pool resource, which is characterized by its shared nature and vulnerability to overuse (Gordon 2000; Hardin 1968). Without proper water management, including formal regulations and well-defined ownership rights, groundwater often becomes overexploited, even during periods without drought (Brozović, Sunding, and Zilberman 2010; Edwards et al. 2016; Pfeiffer and Lin 2014). Overexploitation can deplete the resource faster than it is naturally replenished, ultimately leading to declining water tables and drying wells. Alarmingly, approximately half of the world's major aquifers are showing signs of rapid depletion (Richey et al. 2015; Rodell et al. 2018).

Deforestation presents another significant threat to global water resources. It can reduce precipitation, soil moisture, and the potential to recharge groundwater (Smith et al. 2023). GCEW (2024) highlights how deforestation and other land use changes can disrupt the water cycle and exacerbate local water scarcity.

Attributing TWS changes to specific drivers can be challenging, but examining the sources of TWS loss provides insights into the significance of various factors. This report estimates that annual freshwater loss in nonglaciated drying continental regions is increasing each year and has now exceeded the loss from melting glaciers and ice caps (excluding Antarctica and Greenland). Combining GRACE data with the global hydrological model WaterGAP 2.2d, analysis for this report estimates that in nonglaciated drying regions the single largest contributor to water storage loss comes from the depletion of groundwater (68 percent), followed by depletion of surface water (18 percent), soil moisture (9 percent), and snow water (5 percent). Detailed information on global hydrological modeling can be found in technical appendix A (online).[2]

The following sections delve deeper into the relationship between human activities and freshwater storage changes on a global scale, in particular by integrating down-scaled TWS data with socioeconomic indicators. Findings from these analyses highlight the link between anthropogenic pressures—such as agricultural practices, deforestation, and inadequate water resources management—and the decline in freshwater resources. These findings underscore the significant opportunity to implement sustainable water management strategies to slow the pace of continental drying.

Land use change

Human activities have profoundly transformed the global landscape, often reshaping natural ecosystems to meet agricultural, industrial, and urban demands. Irrigation has boosted yields on rainfed land and increased food supplies (Faurès, Hoogeveen, and Bruinsma 2002; Sarsons 2015), but it is also the largest consumer of water, accounting for about 70 percent of the freshwater diverted by human activity, with almost 50 percent supplied from groundwater (Siebert et al. 2010). Numerous studies have documented the correlation between historical irrigation practices and substantial groundwater depletion, especially in regions heavily reliant on agriculture (Dalin et al. 2017; GCEW 2024).

Forests function as natural reservoirs and filters, playing a crucial role in storing and purifying water. However, global deforestation has disrupted these critical hydrological processes (GCEW 2024). From 2010 to 2015, tropical forests shrank by 5.5 million hectares annually while temperate forests expanded by 2.2 million hectares annually (Zhang and Wei 2021). Although the effects of deforestation on water yields—specifically, the volume of water in streamflow—are still a topic of debate (Filoso et al. 2017), studies have associated deforestation with approximately 4 percent of the recent drying observed in the Amazon (Staal et al. 2020) and with decreased access to clean drinking water, equivalent to a 9 percent decrease in rainfall, in Malawi (Mapulanga and Naito 2019).

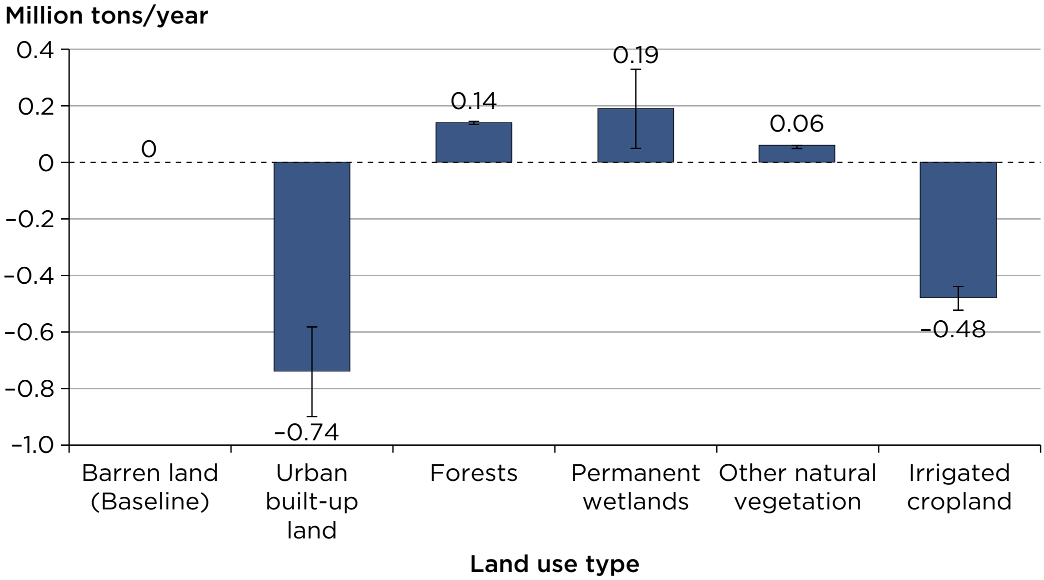
Wetlands also play an essential role in natural water retention and purification (Bring et al. 2020; Lv et al. 2019; Pal and Talukdar 2018), yet the scale of wetland degradation is even more alarming. Since 2002, the global area of permanent wetlands has diminished by about 468,000 km^2, a 24 percent reduction, accounting for approximately 21 percent of all wetlands that have existed since 1700 (Fluet-Chouinard et al. 2023). The primary causes of these losses include wetland drainage for upland croplands (about 61.7 percent of total loss), conversion to flooded rice fields (18.2 percent), urban development (8.0 percent), forestry (4.7 percent), wetland cultivation (4.3 percent), pasture (2.0 percent), peat extraction (0.9 percent, according to Fluet-Chouinard et al. 2023), and the broad-scale disappearance of groundwater (Rohde et al. 2024).

Urban expansion frequently results in the conversion of natural and agricultural lands into urban spaces, diminishing forest coverage. In addition, urban development creates roads and buildings that prevent water from soaking into the ground, reducing natural groundwater recharge and soil moisture. Urban areas also experience increased groundwater abstraction for industrial and commercial activities, further depleting groundwater resources (Rodella, Zaveri, and Bertone 2023). High-resolution mapping of global land use reveals that urban areas have expanded by 50,000 km^2, a 6 percent increase since 2002. Although urban land accounts for only a small fraction of total land area, urbanization is anticipated to continue its upward trend, with 68 percent of the global population projected to reside in urban areas by 2050, up from 55 percent in 2018.

By overlaying land use and TWS data, this report's analysis indicates that the type of land use in 2002 significantly influenced the trajectory of local freshwater availability from 2003 to 2022 (refer to figure 1.2 and box 1.3).[3] Specifically, compared with barren land, a cell with an additional 1 percent of land, or approximately 25 km^2, allocated for urban use will experience an accelerated TWS depletion rate of 0.74 million tons per year over the next two decades. Furthermore, if a cell has an additional 1 percent of land removed from forests, it will experience an accelerated TWS depletion rate of 0.14 million tons annually, assuming all other factors remain constant. Similarly, a 1 percent reduction in wetland area is correlated with an accelerated TWS depletion rate of 0.19 million tons per year under the same conditions. Additionally, allocating an extra 1 percent of land to irrigation results in an accelerated TWS depletion rate of 0.48 million tons per year within that cell. These findings highlight the critical impact of land use changes on TWS depletion.

Land use decisions are a key driver of continental drying in nonglaciated areas.

FIGURE 1.2 **Impact of 1 percent change in land use type in 2002 on TWS trends, 2003–24**



Source: World Bank.
Note: This figure shows the estimated impact of a 1 percent change in the respective land use type in 2002 (equivalent to approximately 25 km^2 on average) on the grid cell's TWS trend from 2003 to 2024, with barren land serving as the baseline. "Other natural vegetation" includes grasslands, savannas, and shrublands. TWS = terrestrial water storage.

BOX 1.3

Untangling the link: The impact of land use change on freshwater availability

Understanding the effects of land use on freshwater availability is not straightforward. Land use is an endogenous decision of society. Taking irrigation as an example, on the one hand, intensive irrigation and excessive water extraction can contribute to the depletion of terrestrial water storage (TWS). On the other hand, changes in water availability can influence the decisions for irrigation development and land use. For example, during prolonged droughts, local populations may respond to decreased water resources by converting more land to agriculture in an effort to offset the loss of productivity on existing

(continued)

BOX 1.3

Untangling the link: The impact of land use change on freshwater availability *(continued)*

cropland (Damania et al. 2017). Thus, using contemporaneous data on land use and TWS can capture both how initial land use decisions affect water resources and how changes in water availability influence land use.

To estimate the impact of land use on water resources, this report estimates the effects of initial land configurations in 2002 on subsequent TWS trends from 2003 to 2024. By focusing on land use data from this earlier time, land use decisions are plausibly exogenous—independent of and unaffected by the TWS outcomes in the decades that follow. This approach helps mitigate endogeneity issues, whereby variables may be influenced by the outcomes they aim to explain, and it thus provides a more accurate picture of how land use configurations influence TWS over time.

Pricing distortions

Accelerated TWS depletion in intensively irrigated cropland is significantly influenced by distortions in water and energy pricing. Water is rarely priced or metered for agricultural water users because irrigation has historically been subsidized to meet other policy objectives, including poverty alleviation, productivity gains, and food security. Evidence suggests that farmers perceive metering as a precursor to regulation or pricing, which increases input costs and may threaten competitiveness in regional and global value chains (Hellegers and Davidson 2024). Where water pricing exists, it often relies on fixed cost structures (Chakravorty, Dar, and Emerick 2023). Although fixed pricing offers a practical solution in areas lacking metering infrastructure, it does not encourage water conservation. As noted by Chakravorty, Dar, and Emerick (2023), only 26 of 80 countries with available water pricing data use volumetric pricing. When irrigation costs bear no relation to actual consumption, farmers are left with little motivation to adopt water-saving technologies or modify their farming practices in ways that could reduce water use.

In regions lacking effective agricultural water pricing, the cost of extracting groundwater aligns solely with the energy needed for pumping

(Badiani-Magnusson and Jessoe 2018; Burlig, Preonas, and Woerman 2020; Fishman et al. 2016). The absence of a price signal for water encourages consumers to extract until the marginal benefit of an additional unit of groundwater equals the net energy extraction costs. Consequently, energy subsidies—especially those for the electricity used in groundwater pumping—further diminish the cost of groundwater, exacerbating the problem of groundwater depletion (Aeschbach-Hertig and Gleeson 2012). Underpriced irrigation not only triggers overpumping but also incentivizes farmers to cultivate more water-intensive crops (Sayre and Taraz 2019; Sekhri 2011).

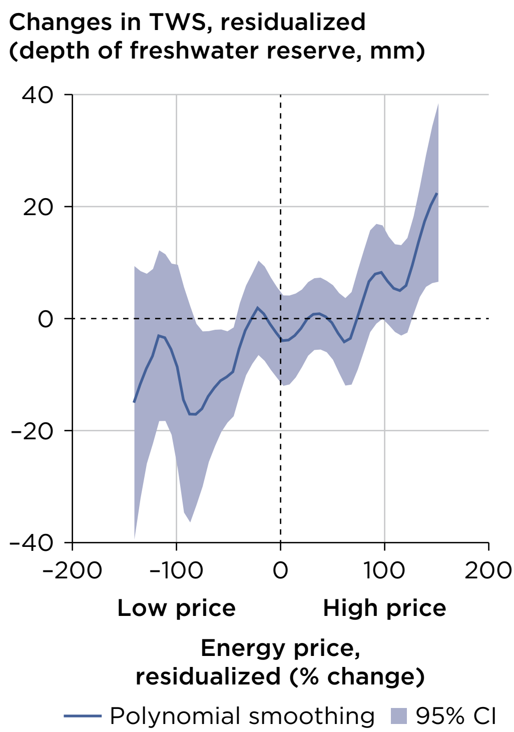
Research indicates that farmers are responsive to the cost of irrigation water. Badiani and Jessoe (2013) observed that a 10 percent increase in electricity subsidies resulted in a 6.6 percent rise in groundwater extraction in India. Similarly, Chakravorty, Dar, and Emerick (2023) demonstrated that water pricing is pivotal in the adoption of water conservation technologies. In Bangladesh, use of the water-saving technique known as alternate wetting and drying increased by 21 percent when villages transitioned from fixed charges to volumetric pricing. Even with the implementation of efficient irrigation technologies, pricing remains a critical element in water conservation. Fishman, Giné, and Jacoby (2023) found that, when a group of smallholders received a 90 percent subsidy on their drip irrigation installation, no reduction in groundwater pumping was observed after three years; given the minimal costs associated with pumping, farmers opted to maximize use and sell the excess water to neighboring landowners rather than conserve it.

This report uses annual energy inflation data from the World Bank's Global Consumer Price Index data set, covering 142 countries, and identifies a statistically significant negative correlation between energy prices and the rate of TWS depletion in countries with intensive irrigation, defined as those with more than 20 percent of cropland irrigated.[4] As shown in figure 1.3, in countries that depend heavily on irrigation, lower energy prices are associated with a faster decrease in water levels and higher energy prices with a slower depletion rate. In contrast, the impact of energy prices on TWS is statistically insignificant in countries with minimal irrigation. Technical appendix A (online) provides additional details regarding the data and methodology used in the analysis.

Notably, not all irrigation systems depend on groundwater pumping. Gravity-fed irrigation systems require no energy inputs for water transport. For these systems, fluctuations in energy prices may have little to no effect on TWS levels, which can lead to some noise in the data regarding the relationship between energy prices and water storage. Nevertheless, a negative correlation between energy prices and TWS levels persists, indicating that energy subsidies and the general underpricing of water incentivize groundwater extraction, ultimately contributing to the depletion of freshwater resources.

Addressing pricing distortions can help preserve freshwater resources.

FIGURE 1.3 Impact of energy pricing on freshwater reserves in irrigation-intensive countries



Source: World Bank.
Note: This figure illustrates the relationship between changes in energy prices and changes in freshwater reserves (measured by TWS). Both energy price and TWS level are residualized, controlling for annual average temperature and precipitation (and their polynomial functions up to the third order), country fixed effects, and year fixed effects. Irrigation-intensive countries are defined as countries having more than 20 percent of their cropland irrigated. The shading indicates 95 percent CIs, representing the precision of the estimates. CI = confidence interval; TWS = terrestrial water storage.

Lack of integrated water management

The previous section underscores that water outcomes are often shaped by decisions made outside of the water sector, particularly decisions regarding land use. Therefore, it is important to coordinate the management of land, water, and related resources while balancing the competing demands of various sectors, including agriculture, urban development, and conservation, to safeguard water resources.

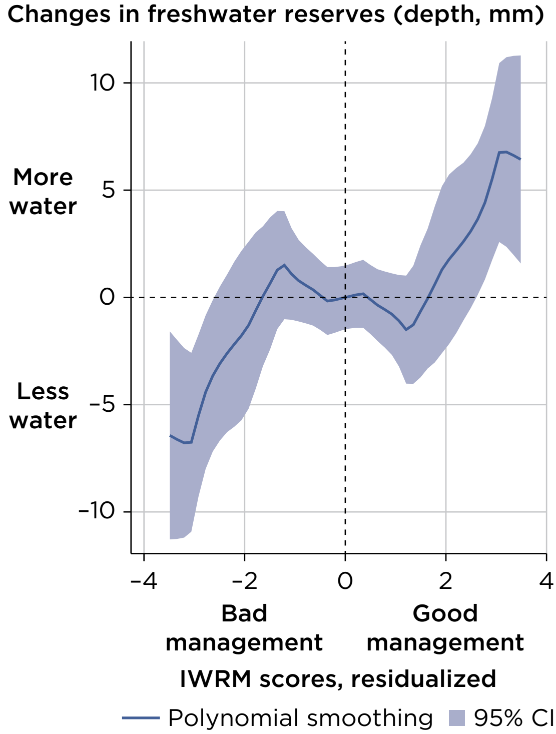
The concept of managing water resources using integrated approaches—integrated water resources management (IWRM)—has been incorporated into the Sustainable Development Goals (SDGs) as reflected in SDG indicator 6.5.1,[5] which tracks the degree of IWRM implementation across countries. This indicator has been measured over three data collection rounds, covering 173 countries in 2017, 186 countries in 2020, and 183 countries in 2023. A country's IWRM score is determined by performance on four key dimensions: enabling environment (laws, policies, and plans supporting IWRM), institutions and participation (institutional capacity and stakeholder engagement), management instruments (data collection and planning tools), and financing (investments and funding for IWRM efforts and infrastructure). The scoring uses a scale ranging from 0 to 100, with higher scores reflecting more comprehensive and effective IWRM implementation. The data on the degree of IWRM implementation are collected from country self-assessments and validated through stakeholder consultations.

This report evaluates the relationship between IWRM scores and average TWS depletion rates over the three years after the survey. The findings reveal that inadequate IWRM implementation accelerates TWS depletion, whereas adequate IWRM implementation leads to more sustainable TWS outcomes, all else equal (refer to figure 1.4).[6] Specifically, a decline of 1 standard deviation in a country's IWRM score is, on average, associated with an accelerated TWS decline of 0.011 km^3 per year per cell, that is, 11 million tons of water per year per cell, or a 0.36 standard deviation change in the rate of depletion.

To avoid potential biases associated with self-reporting that could confound the estimation results, additional analysis was conducted to compare TWS trends of extremely poor performers with those of other performers.[7] The results show that countries with IWRM scores lower than 30 experienced an average TWS decline that occurred two to three times faster than that of the countries with more robust IWRM implementation. Overall, the evidence indicates that enhancing IWRM can play a pivotal role in mitigating water depletion and fostering environmental sustainability.

Strengthening integrated water resources management can help preserve freshwater resources

FIGURE 1.4 Impact of IWRM on freshwater reserves



Source: World Bank.

Note: This figure illustrates the relationship between the score of IWRM and changes in freshwater reserves (measured by TWS). The x axis represents a country's degree of IWRM implementation for a given survey round; the y axis shows the corresponding TWS trend in the three-year period after the survey round. Both variables are residualized, controlling for the country's annual average temperature and precipitation (and their polynomial functions up to the third order), country fixed effects, and survey-year fixed effects. The unit of the y axis refers to the equivalent depth of TWS in millimeters (that is, the depth of water when it is uniformly distributed across each 0.5° grid cell). The shading indicates 95 percent CIs, representing the precision of the estimates. CI = confidence interval; IWRM = integrated water resources management; mm = millimeters; TWS = terrestrial water storage.

Conclusion

Using observational satellite data from GRACE, this chapter highlights an alarming trend of continental drying—a persistent decline in freshwater availability across vast landmasses. This drying is driven by a combination of

a changing climate and unsustainable water and land practices.
The potential risks of continental drying are profound: it can reduce agricultural productivity, heighten competition for water resources, and, in extreme cases, trigger ecosystem collapse and large-scale emigration. The next chapter explores the cascading impacts of continental drying on people, the economy, and the environment.

Notes

1. Areas under drying conditions (or dry anomalies) are spread across different regions each year.
2. Technical appendixes A through E are available online at https://hdl.handle.net/10986/43683.
3. The analysis controls for local precipitation and temperature influences as well as other unobservable and time-invariant location-specific characteristics. Regions where ice sheet and glacier melting have caused significant TWS decreases, such as Greenland, the Gulf of Alaska, and Patagonia, are removed from the sample. Refer to box 1.3 and technical appendix A (online) for details on the methodology.
4. Energy prices are lagged to address potential endogeneity between energy costs and the irrigation-driven demand for energy. The findings remain robust after controlling for variables such as temperature, precipitation, time-invariant country characteristics, and year fixed effects, along with alternative definitions of irrigation intensity. Specifically, 40 countries are classified as irrigation-heavy on the basis of the criterion that more than 20 percent of their cropland is primarily irrigated. Alternatively, a country is deemed irrigation-heavy if it has more irrigated cropland than rainfed cropland. The results are robust under both definitions.
5. UN SDG Indicator 6.5.1. 'Degree of Integrated Water Resources Management Implementation (0-100)," https://www.unwater.org/our-work/sdg-6-integrated-monitoring-initiative/indicator-651-degree-integrated-water-resources.
6. The analysis uses country-level panel data and controls for temperature, precipitation, and country and survey-year fixed effects.
7. In 2017, about 19 percent of countries were classified as having a low or very low level of IWRM implementation, with scores below 30. This percentage decreased to about 12 percent in 2020, and, by 2023, about 8 percent of surveyed countries remained in the low implementation category.

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