

# *Annual Review of Environment and Resources*

## Freshwater Scarcity

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### Keywords

freshwater, water scarcity, peak water, water use, water demand,  
water indicators

### Abstract

The availability and use of fresh water are critical for human health and for economic and ecosystem stability. But the growing mismatch between human demands and natural freshwater availability is contributing to water scarcity, affecting industrial and agricultural production and a wide range of social, economic, and political problems, including poverty, deterioration of ecosystem health, and violent conflicts. Understanding and addressing different forms of water scarcity are vital for moving toward more sustainable management and use of fresh water. We provide here a review of concepts and definitions of water scarcity, metrics and indicators used to evaluate scarcity together with strategies for addressing and reducing the adverse consequences of water scarcity, including the development of alternative sources of water, improvements in water-use efficiency, and changes in systems of water management and planning.

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## INTRODUCTION

The importance of fresh water for humans and ecosystems and the dramatic spatial and temporal differences in water availability around the world have led to great interest in understanding and measuring water scarcity. Problems associated with the lack of fresh water include adverse impacts on human and ecosystem health; constraints on industrial and agricultural production; and a wide range of social, economic, and political disruptions, including poverty and violent conflict over access and control of water.

Ensuring that adequate quantities and qualities of water are available is at the heart of many of the objectives of the global water community and enshrined in Goal 6 of the United Nations Sustainable Development Goals (SDGs): Ensure availability and sustainable management of water and sanitation for all. SDG Target 6.4 explicitly says, “By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity” (1).

Put most simply, water scarcity is a shortage in the amount of water required to meet a specific water demand. The goal of research in this area over the past several decades has been to define

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and measure water scarcity and ultimately develop strategies for overcoming it. We provide here a review of concepts and definitions of water scarcity and their application to the sustainable management of the world's freshwater resources.

## DEFINING WATER SCARCITY

One of the core characteristics of the Earth's freshwater resources is the great variability in its distribution in space and time. The hydrologic cycle moves water between stocks such as the oceans, icecaps, glaciers, and groundwater in flows such as evaporation, transpiration, rainfall, and river runoff. These movements vary through natural fluctuations driven by complex climatic factors. As a result, parts of the planet are naturally dry, some are naturally wet, and all experience dynamic changes in water availability. Natural ecosystems have evolved and adapted to this natural variability.

Scarcity in the context of human social, economic, and health needs arises in particular places or at particular times when human demand for water may exceed the stocks or flows of water on which those demands depend. Water supplies are affected by both natural hydrologic variability and a wide range of human activities that modify the hydrologic cycle, such as contamination of stocks, the construction and operation of water infrastructure, and human-caused climate change. Human demands for water also change over time, driven by population growth, economic activities, and social priorities and preferences.

Globally, the total stock of water is hundreds of thousands of times larger than even the largest estimates of human water demands. However, not all the water in those stocks is accessible, and there are great disparities in when and where humans require fresh water to satisfy demands. In this sense, the following discussion of water scarcity focuses on the human and natural drivers that lead to mismatches between supply and demand.

Most discussions about water scarcity are actually discussions about regions that are approaching peak renewable water limits, where the effective capture and use of fresh water is near the total renewable supply (2). Major river systems such as the Colorado River, the Nile, the Huang He, and the Jordan, among others, are all reaching peak water limits beyond which no additional withdrawals are possible. When peak renewable water limits are reached in a watershed where demand is thought to be increasing, scarcity ensues and either additional water sources must be found through transfers from other basins, desalination, or reuse or existing water use must be made more efficient to permit increased production of desired goods and services within the limits of available supply. Not all water resources are considered renewable, however. When a stock of water is used faster than it is naturally recharged, such as in regions where groundwater is overdrafted, peak nonrenewable water limits occur, and the resource becomes physically or economically more costly to obtain over time. At this point, extraction begins to decline, conditions of scarcity increase, and substitutes must be found (2).

## WATER SUPPLY

Two of the most common elements in the universe—hydrogen and oxygen—combine to form water, ubiquitous throughout the solar system. Water ice has been found in dark craters on Mercury and our moon. There is water vapor in the atmosphere of Venus. Mars has clouds, polar ice caps, subsurface brines and lakes, and evidence of vast ancient oceans. Spacecraft and Earth-based observers have identified water molecules in the atmospheres of Jupiter and Saturn, and some of their many moons are known to have ice mantles and subsurface oceans of liquid water that have been observed venting to space. The ice giants of Uranus and Neptune are almost

entirely composed of water, and even the frozen comets and rocky asteroids circling the sun out to the very edges of the solar system have water in many different forms (3, 4).

Only Earth, however, circling in what's known as the Goldilocks zone—the distance from the sun just right for the conditions suitable for life as we know it—has vast quantities of water in liquid oceans, lakes, and soils, circulating atmospheric stocks of water vapor, and surface ice that helps regulate the planet's temperature (5). Scientific debate continues about where the Earth's water originated, whether it came with the first interstellar gases and dust that coalesced into our planet approximately 4.5 billion years ago or whether the water came later through the bombardment of large and small water-bearing planetesimals from the outer reaches of the solar system (3). Whatever its origin, our water resources were critical for the formation of life on Earth and remain critical for the continued survival and functioning of ecosystems and human civilization.

## Stocks and Flows of Water

The total stock of water on Earth is uncertain. Recent studies have suggested that significant volumes of water may be mixed under extremely high pressure in the Earth's core with iron and silicate melts and that the core may act as a large reservoir containing most of the planet's water (6). Although of great scientific interest, that water plays no role in the dynamic circulation of water, vapor, and ice on the surface or in questions about water scarcity related to human needs.

Of far more importance are the stocks and flows of water on, or close to, the Earth's surface. Uncertainties also accompany the estimates of water in these more accessible stocks and flows, but **Table 1** provides two estimates of the quantities of water in components of the hydrologic cycle. Natural variability of all of the world's hydrologic flows; the difficulty of evaluating hidden, hard-to-measure groundwater volumes; the lack of accurate real-time river flow estimates, and even large uncertainties in the volume of the oceans all contribute to the difficulty of determining accurate planetary and regional water balances.

The largest stock of water is in the oceans, estimated to be approximately 1,340,000,000 cubic kilometers (km<sup>3</sup>) or 97.5% of the total volume of water on the Earth's surface. This water is too salty for nearly all domestic and agricultural uses. Of the Earth's fresh water, the largest stocks are

**Table 1 Recent estimates of global stocks of water (1,000 km<sup>3</sup>)<sup>a</sup>**

Stock	Quantity [from Oki & Kanae 2006 (7)] <sup>b</sup>	Quantity [from Trenberth et al. 2011 (8)] <sup>c</sup>
Oceans	1,338,000	1,335,040
Ice and glaciers	24,064	26,350
Groundwater	23,400	15,300
Permafrost	300	22
Lakes	175	178 (lakes and rivers)
Soil moisture	17	122
Wetland	17	NA
Water vapor over oceans	10	12.7 (land and ocean water vapor)
Water vapor over land	3	NA (included in number for water vapor over oceans)
Rivers (stock)	2	NA (included in number for lakes)
Biota	1	NA

Abbreviation: NA, not applicable.

<sup>a</sup>Water in the Earth's crust and mantle is not included in these estimates.

<sup>b</sup>The Oki & Kanae estimates are synthesized from various long-term estimates.

<sup>c</sup>The Trenberth et al. estimates are based on observational data for the years 2002 to 2008.

**Table 2** Estimates of fluxes of water (1,000 km<sup>3</sup>/year)<sup>a</sup>

Flux	Oki & Kanae 2006 (7)	Rodell et al. 2015 (11) <sup>b</sup>	Trenberth et al. 2011 (8) <sup>c</sup>	Mueller Schmied et al. 2016 (10) <sup>d</sup>
Evapotranspiration from oceans	436.5	449.5 (+/- 22.2)	426	ND
Evapotranspiration from land	65.5	70.6 (+/- 5.0)	74	67.6
Precipitation over oceans	391	403.5 (+/- 22.2)	386	ND
Precipitation over land	111	116.5 (+/- 5.1)	114	109
Atmospheric transport from oceans to land	45.5	45.8 (+/- 4.4)	40	ND
River flow to oceans	45.5	45.9 (+/- 4.4)	40	40.7

Abbreviation: ND, no data.

<sup>a</sup>Not all references provide uncertainty ranges.

<sup>b</sup>Estimates include optimization to close the water balance.

<sup>c</sup>Estimates are based on observation data for 2002 to 2008.

<sup>d</sup>Continental water balances are averaged from five model variants and the years 1971 to 2000. This reference does not provide ocean-related evapotranspiration or precipitation.

icecaps and glaciers and relatively shallow groundwater. Much of this water is also not physically or economically accessible for human use, contributing to the contradictory idea that there could be water scarcity on a planet covered in water.

Numerous studies have been conducted of major natural flows between these stocks of water in the form of precipitation, evapotranspiration, and river runoff, including combinations of observations and model estimates (9–12). Water-balance components vary from year to year and there are uncertainties associated with the difficulty of measurement, but the current estimate of total precipitation over land is approximately 110,000 cubic kilometers per year (km<sup>3</sup>/year), natural evapotranspiration is approximately 68,000 km<sup>3</sup>/year, and river discharge into the oceans and inland sinks is approximately 40,000 km<sup>3</sup>/year. The remainder is net human consumption of water, which then contributes to evaporation, surface, and groundwater flows. **Table 2** shows the average estimates of components of the global water balance from four sources.

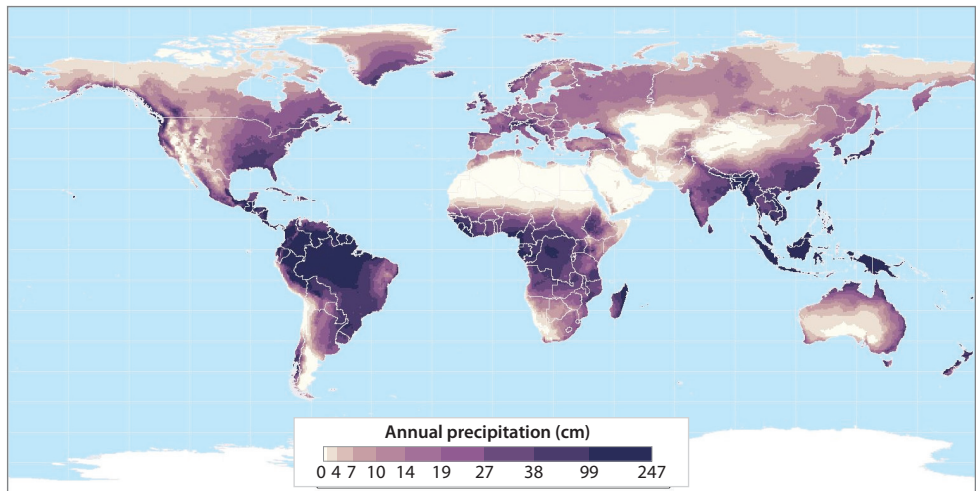
Humans are increasingly affecting global and regional water cycles. We extract water from rivers, lakes, and aquifers. We transport water from one watershed to another. We apply vast quantities of irrigation water that evapotranspires into the atmosphere or infiltrates into the ground. We build massive dams on rivers that store water and change the timing and magnitude of river flows into the oceans. Despite the importance of water, no comprehensive global system for monitoring or measuring human influence on the Earth's stocks and flows of water exists (11).

## Geographical Distribution

As noted above, the distribution of water around the planet is highly uneven and variable because of the way the circulation of the atmosphere collects, moves, and discharges moisture. The atmosphere collects moisture through evaporation from the oceans and land surfaces and transports that moisture in various pathways that contribute to precipitation back to the land and oceans. Three major atmospheric processes dominate the transfer of moisture from one region to another: atmospheric rivers, low-level jet streams, and tropical cyclones/hurricanes (13). These processes lead to dramatically different levels of precipitation by region, as **Figure 1** shows.

## WATER DEMAND

Water scarcity only makes sense in the context of water demands. In early efforts to define and measure demand, the simplest approach was to report the total volume of water withdrawn from



**Figure 1**

The uneven distribution of precipitation around the world. Figure adapted with permission of the Center for Sustainability and the Global Environment, Nelson Institute for Environmental Studies, University of Wisconsin-Madison. Data represent the 30-year running mean from 1960–1990 from CRU 0.5° dataset.

natural surface (and sometimes groundwater) systems to meet current needs and to assume new water withdrawals would be required to meet projected demand increases.

As the understanding of water use has improved, distinctions among different kinds of use have developed. Water use can be categorized as withdrawals and as consumptive or nonconsumptive (14, 15). Withdrawal typically refers to all water taken from a source and can be directly measured. Consumptive use commonly refers to water that is made unavailable for reuse in the basin due to evaporation from land and water surfaces, incorporation into plant biomass, transfer to another basin, seepage to a saline sink, or contamination. Consumptive use levels are typically calculated using assumptions. Nonconsumptive use refers to water withdrawn from an available supply but that remains available for reuse within the same basin.

Less common, although equally important, water use can also be divided into productive and unproductive uses (sometimes referred to as beneficial and nonbeneficial uses) (16). Productive uses are those that contribute directly to economic and agricultural value but can also include evaporative losses needed for crop health and applied water that leaches harmful salts from the root zone. Unproductive uses include transpiration from weeds and evaporation from windblown losses from sprinklers and wet soils, and evaporation from the surfaces of reservoirs and canals. Unproductive consumptive losses are rarely measured or reported and often not categorized in water balances, but they represent water that could be shifted to productive use (14).

Different kinds of demands require different kinds of water. To address these differences, the concepts of blue, green, and gray water demand have been developed. Blue water refers to available surface and groundwater, green water is water available as precipitation, and gray water is an indicator of the degree of water pollution and defined as the volume of fresh water needed to assimilate water pollutants based on water-quality standards (17). These concepts now play a fundamental role in helping the water community improve understanding of issues related to water scarcity and water management.

## Global and Regional Water Withdrawals

Data on water withdrawals by regions and different economic sectors are among the most sought after but are often the least reliable and most inconsistent of all water resources information. The Food and Agriculture Organization of the United Nations maintains the AQUASTAT database, which has tried to standardize estimates of water withdrawals by country. These data, however, come from a variety of sources and include both measured and modeled estimates, data reported at irregular intervals, and large data gaps. Despite their limitations, they remain among the most comprehensive datasets available, and we examine them here.

Within the AQUASTAT database, water withdrawals are divided into three major categories: agriculture, industry, and municipal/domestic, although water-accounting systems are inconsistent. Some additional water is consumed by evaporation from artificial lakes and reservoirs, but the amounts are relatively modest compared to the intentional human withdrawals described below:

- Agricultural water withdrawals consist of water used for irrigation, livestock watering and cleaning, and aquaculture. Water for processing agricultural products is included under industrial or municipal water withdrawals. In rural areas, agricultural water withdrawals frequently include water for domestic purposes.
- Industrial water withdrawals consist of water used by self-supplied industries not connected to a public distribution network for such purposes as fabricating, processing, washing, diluting, cooling, or transporting a product; water incorporated into a product; or water used for sanitation needs within the manufacturing facility.
- Municipal withdrawals are a broad category that includes water for domestic uses, as well as water provided by a municipality or other public supplier for commercial, industrial, and institutional purposes.

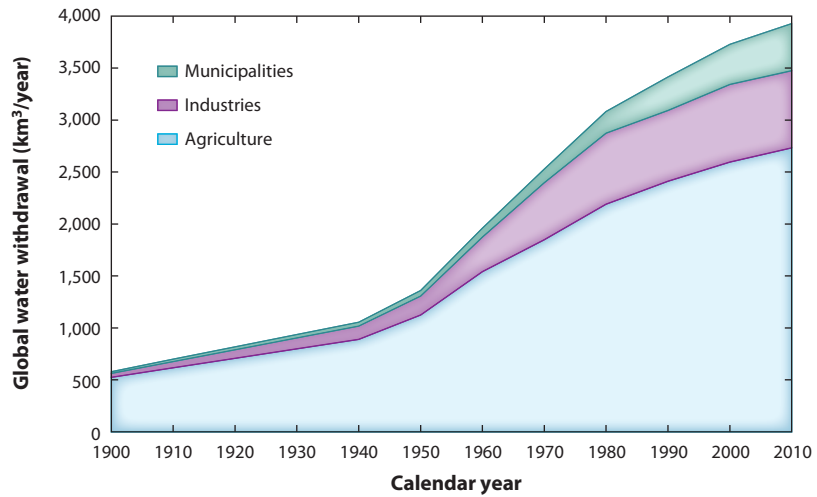
Around 2010, the most recent year for which data are available, agriculture accounted for 69% of global water withdrawals, followed by self-supplied industry (19%) and municipalities (12%) (18). These ratios, however, are subject to significant regional variability. In Africa and Asia, for example, agriculture accounts for more than 80% of water withdrawals, compared to 65% in Oceania, 48% in the Americas, and 25% in Europe. By contrast, industrial water withdrawals are relatively high in Europe (54%) and the Americas (37%), compared to 15% in Oceania, 10% in Asia, and only 4% in Africa. Regional variability in municipal withdrawals ranges from 9% in Asia to approximately 20% in Oceania and Europe.

## Trends in Water Withdrawals

Global water withdrawals increased nearly sixfold between 1900 and 2010 (**Figure 2**) (18). The period of most rapid growth was between 1950 and 1980, when global water withdrawals increased by a factor of 2.5. There was a similar trend for consumptive use of water, including surface and groundwater use (19). The rate of growth began to slow in 1980, and there is some indication that water withdrawals started to slow around the year 2000. Between 2001 and 2010, global water withdrawals increased by only 2.7%, compared to an average increase of 30% in each 10-year period spanning 1951 to 1960, 1961 to 1970, and 1971 to 1980. Changes in water withdrawals also vary by region. **Figure 3** shows global water withdrawals broken up by three major economic groups: Brazil, Russia, India, China, and South Africa (BRICS); the Organisation for Economic Co-operation and Development (OECD); and the rest of the world (ROW).

## Forecasting Water Demand

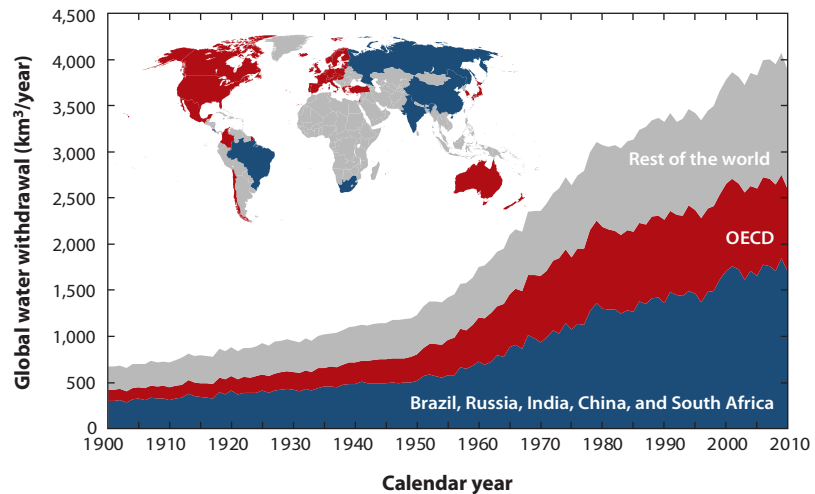
Water managers routinely make long-range projections of future water demand as part of water-system planning. These projections are used to develop infrastructure investment plans, with



**Figure 2**

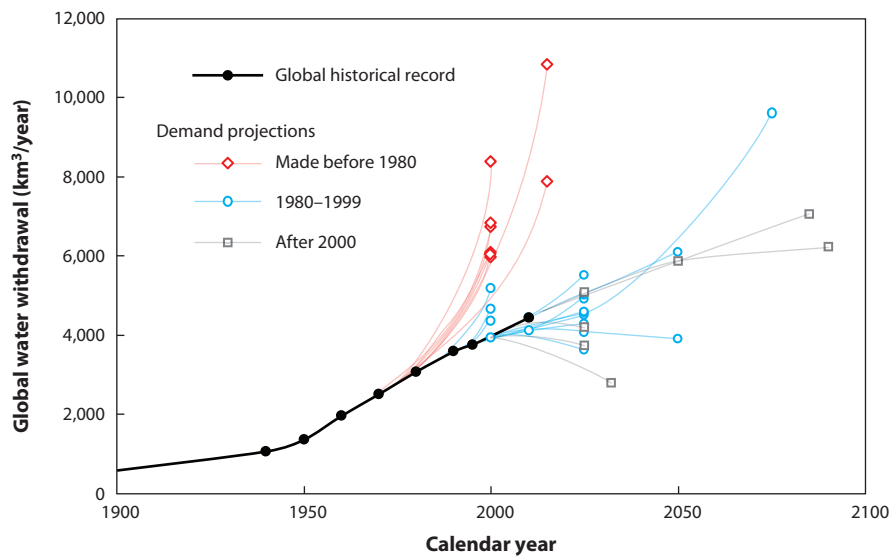
Global water withdrawals (km<sup>3</sup>/year) by sector from 1900 to 2010. Global water withdrawals are dominated by irrigated agriculture. Data from References 18 and 20.

implications for regional water supply, treatment infrastructure, and costs to consumers. For much of the twentieth century in industrialized nations, water demand forecasts were typically based on projections of population and economic growth combined with historical rates of per capita water use. Thus, as populations grew, water demand was always forecast to grow. From the late 1960s through the 1970s, various analysts projected that global water withdrawals by 2000 would double or even triple (24–26). Projections made in the 1980s and 1990s also showed dramatic increases



**Figure 3**

Global water withdrawals, total and by region. Data from References 21–23. This figure shows global water withdrawals broken out by three major economic groups: Brazil, Russia, India, China, and South Africa (blue); the Organisation for Economic Co-operation and Development (OECD, red), and the rest of the world (grey).

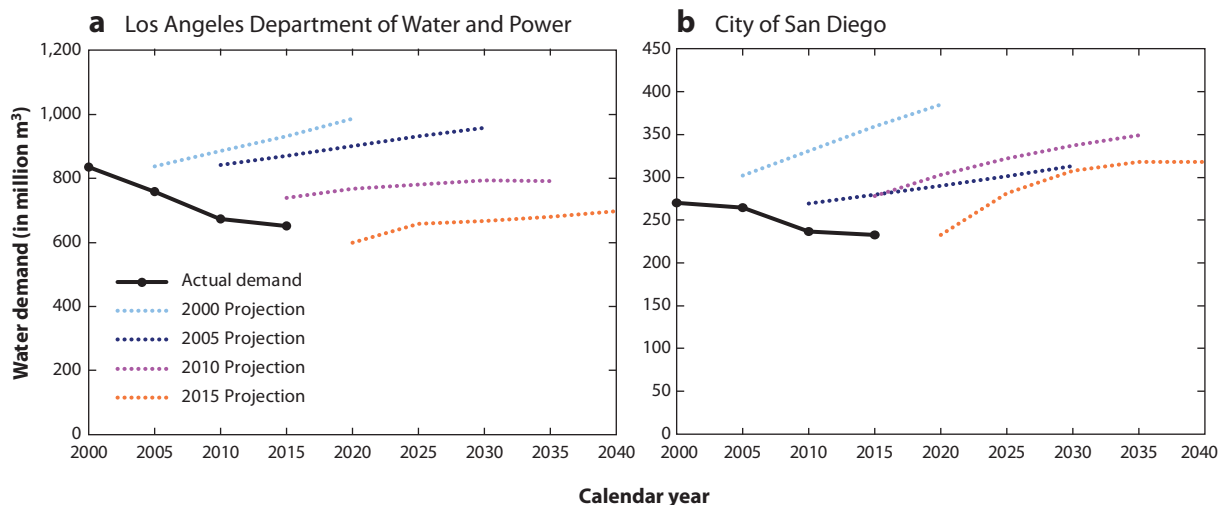


**Figure 4**

Various global water demand forecasts made before 1980 (*red*), between 1980 and 1999 (*blue*), and after 2000 (*gray*) by the year of the forecast, compared to historical global water withdrawals (*black*). Each data point represents an individual future water-use projection with the line beginning at the year the projection was published. The early projections all anticipated very large increases in water withdrawals. The most recent projections show a leveling off or even a decline in water withdrawals, recognizing recent decoupling of water use from economic and population growth. Figure adapted with permission from Reference 32.

in global water demands, even as actual withdrawals were beginning to level off (20, 27, 28). **Figure 4** shows a series of global water demand forecasts made before 1980, between 1980 and 1999, and after 2000 by the year of the forecast, compared to historical global water withdrawals. With a few rare exceptions, these projections all show large increases in water demands, often far above the level of demand that actually occurred historically. It was not until the turn of the twenty-first century that some models began to incorporate more sophisticated assessments of population dynamics, water-efficiency programs, and actual peak water constraints, showing a slowdown and even the possibility of a leveling off or decrease in total water withdrawals (29–31).

Overestimating future demands is a local and regional problem as well. A review of the accuracy of long-range water demand forecasts was recently conducted for California's 10 largest urban water providers (33). In 2015, these water suppliers served one-quarter of the state's population. Water demands in California have been leveling off and even declining for years, because natural supplies are limited, water-efficiency programs have been aggressively implemented, and the economy has changed, with less water-intensive manufacturing. Yet all 10 water suppliers still consistently projected that future demands will grow, largely because they continue to use inflated estimates of per capita water use and outdated assumptions about the effects of population and economic growth on water demands. Even when water suppliers accounted for constant and sometimes even declining per capita water demand, actual demand declined faster than projected (33). **Figure 5a,b** shows actual and projected water demands for two large California metropolitan areas—all show actual demands consistently below projections. Among the negative consequences of overestimating future water demands are costly financial expenditures for unneeded water supply and treatment infrastructure, higher costs of service for consumers, and unnecessary environmental impacts (33, 34).



**Figure 5**

Most major water systems routinely project increases in demands far above the levels that actually materialize. Here actual water demand for the Los Angeles Department of Water and Power (*a*) and City of San Diego (*b*) is plotted (*solid black line*) against the projections of demands (*dotted lines*)—made in 2000, 2005, 2010, and 2015 for 20 or 25 years in the future. Data from Abraham et al. (33). Despite continuing declines in actual demand, all the projections show rising future demands largely because they continue to use inflated estimates of per capita water use and outdated assumptions about the effects of population and economic growth on water demands. Even when water suppliers accounted for constant and sometimes even declining per capita water demand, actual demand declined twice as fast as projected (33).

## DRIVERS OF SCARCITY

Many factors drive water scarcity, including the basic hydrology of a region, demographics and economics, the level and type of water infrastructure and institutions built to satisfy human demands, and the nature of those demands themselves. We address these key factors here.

### Hydrology

Central to the concept of scarcity is the mismatch between supply and demand. The natural variability of the hydrological cycle creates such mismatches, but in the absence of the human component of water demand, such natural variability simply drives variability in ecosystem type, from rainforest to desert systems. As noted above, the natural hydrologic cycle is highly variable in space and time. Although estimates of global average stocks and flows of water are available (see **Tables 1** and **2**), these averages hide the dynamic fluctuations that can also influence human perceptions of scarcity.

There are many different definitions of drought, including hydrological, meteorological, agricultural, and economic (35, 36). Hydrological and meteorological drought, for example, may be defined as a shortfall of runoff, groundwater, precipitation, or another water-related metric compared to the amount of water expected on average. Agricultural drought may be a shortage of water during a particularly critical time required for the successful production of a crop. A social or economic drought can be defined in the context of a specific social or economic demand for water when that demand cannot be fully met. Ecological drought is a deficit in naturally available water supplies that create stresses across ecosystems. A simple definition of drought

is “the mismatch between the amounts of water nature provides and the amounts of water that humans and the environment demand” (35, p. 3859). The impacts of drought result from the interplay between natural events, the demands people place on water supply, and the fact that human activities can influence both supply and demand.

## Demographic and Economic Factors

In the simplest sense, the role of population- and economic-driven demands is straightforward. With very modest exceptions, water is neither created nor lost on Earth, but simply shifts from one stock to another over time, so the natural availability of water resources over time is fixed. As populations increase, therefore, the amount of water available per capita declines. The simple metric—per capita water availability (water per unit population)—is a common way to measure water scarcity, and numerous indices have been created with variants of it. With population and economic growth, the demand for water has traditionally increased as well, creating measurable and significant new contributors to scarcity and supply/demand imbalances. Economic factors can also drive perceived scarcity when for reasons of poverty people are unable to pay for the water services they need and are deprived of access to those services (37).

It is vital to note that in regions considered water scarce, there are often populations—typically wealthier and socially privileged communities—who do not lack access to adequate basic water services. Conversely, in regions with abundant water, there are communities that do not have access to safe, affordable water—typically poor and marginalized communities (38, 39). This issue of water poverty requires far more attention, because it transcends the issue of physical water availability or scarcity and encompasses issues of economic ability to pay for water (40, 41); questions about public versus private control of water systems (42, 43); differences in access to water technologies and built water systems (44, 45); and entrenched social, political, religious, and racial discrimination (46, 47).

## Infrastructure and Institutions

Even when physical or economic availability of water is not a problem, water scarcity can still occur if inadequate infrastructure exists or problems with institutions and water management systems keep desired water services from reaching the point of demand. Is water scarce when a nearby watershed, spring, or river has abundant water but a community must walk two miles to get it, or when the quality is unsafe? In such cases, the problem may be institutional or infrastructure scarcity, not physical scarcity, and it is addressed not by finding new sources of supply or modifying demand, but by improving the management and infrastructure required to satisfy water demands.

Another aspect of institutional scarcity is when water policy limits the amounts of water that can be used, for example, when efforts to protect and restore ecosystems lead to commitments of water for the environment that might previously have been used by humans. By acknowledging that ecosystems have a right to water left instream, local conditions of scarcity as perceived by humans may worsen. In 1992, the US Congress passed the Central Valley Project Improvement Act, a multipurpose water law that, among other things, mandated that a billion cubic meters of water be dedicated to ecosystem restoration, including improving the health of anadromous fish populations. This law was perceived as creating additional water scarcity challenges for farmers in the region and worsening groundwater overdraft by shifting agricultural water use from surface sources to aquifers, and it has been a contentious issue in California water politics for nearly three decades (48).

## Climate Change

Human-induced climate changes are accelerating. Among the now unavoidable consequences are fundamental changes in the hydrologic cycle, including increases in evapotranspiration rates as temperatures rise, regional shifts in stocks and flows of water and ice, alterations in the intensity and severity of extreme events such as droughts and floods, shifts in the freshwater balances of coastal aquifers and estuaries as sea levels rise, and more (49). Climate changes will also have direct and indirect impacts on water scarcity by changing both the supply and demand of fresh water. Although climate models continue to improve, uncertainties about the detailed long-term implications of climate change for regional and local hydrology remain. Nevertheless, in recent years, the fingerprint of climate changes has been seen in a growing number of water-related areas, including the amount of water delivered by tropical cyclones (50, 51), the depth and severity of droughts (52, 53), alterations of river flows due to melting snow and ice (54, 55), and evaporation losses from reservoirs (56). As climate changes worsen, the risks of water scarcity for hundreds of millions of people are expected to increase, barring major efforts to reduce scarcity risks (9, 57).

## WATER SCARCITY INDICATORS AND METRICS

As human use of water has grown, and as some regions have experienced peak water constraints, numerous attempts have been made to define and measure water scarcity. As many as 150 different indicators of water scarcity have been developed in recent years (58). These efforts have evolved with improvements in our understanding of the nuances of both natural water supply and human and ecological water demands.

### Per Capita Water Metrics

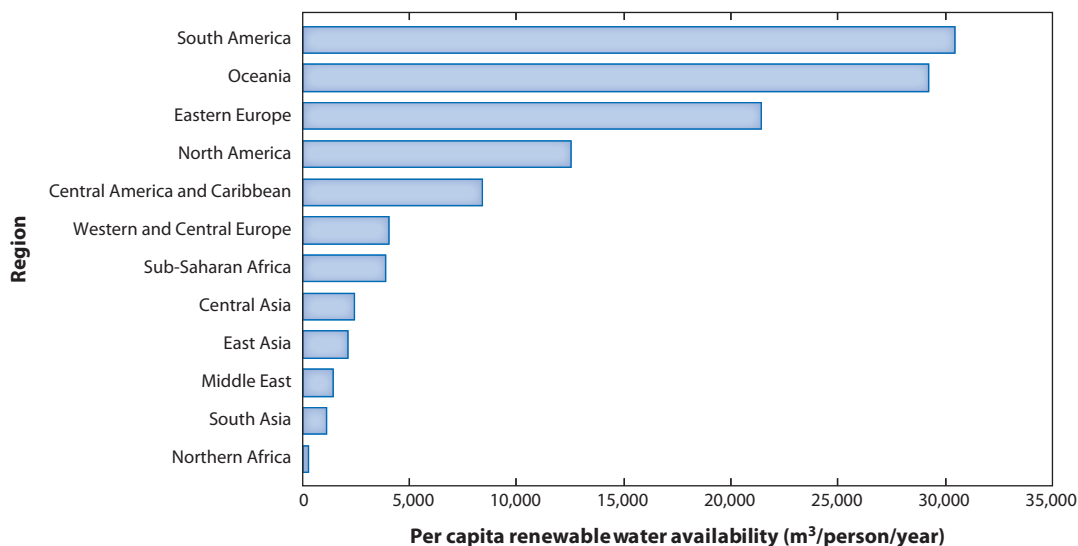
Another way to understand the uneven distribution of renewable freshwater resources is to look at water availability per person, a metric that integrates natural availability with the size of the population needing to be served by that supply. **Figure 6** presents, for the major regions of the world, per capita renewable water availability. Where this metric is low, water scarcity risks—driven by a combination of hydrology and population—are higher.

One of the earliest approaches to quantifying water scarcity adopts this concept of a per capita water availability index. Proposed by Swedish water expert Malin Falkenmark, this metric measures the amount of natural renewable fresh water available in a country as a function of population size. The larger the population trying to manage with each unit of water, the greater the water scarcity (25).

Over time, this metric was inverted to measure how much fresh water is available per unit of population. In this form, 1,700 cubic meters of water per person per year ( $\text{m}^3/\text{p}/\text{year}$ ) was selected as the level above which water shortages are rare and localized; at less than 1,000  $\text{m}^3/\text{p}/\text{year}$ , water constraints begin to affect health, economic development, and well-being; and below 500  $\text{m}^3/\text{p}/\text{year}$  indicates that water availability is a major constraint to economic and human well-being (**Table 3**).

Many people and organizations have relied on the Falkenmark index or a comparable metric of per capita water scarcity to evaluate overall water challenges. In the 1990s, for example, Population Action International used it to rank countries of the world in order of scarcity (61, 62), and it continues to be cited and applied today (19, 63).

Although the Falkenmark metric and others that focus on population are simple and widely used, they have several shortcomings. One problem is the fundamental assumption that all a region's renewable freshwater supply is available for human use without regard for ecosystem water needs. Another problem is that the index assumes a measure of water availability as a proxy for



**Figure 6**

Per capita renewable water availability by region in cubic meters per person per year. Data from Reference 18. The uneven distribution of renewable freshwater resources is apparent when looking at water availability per person by region, a metric that integrates natural availability with the size of the population needing to be served by that supply. The figure presents, for the major regions of the world, per capita renewable water availability. Where this metric is low, water scarcity risks—driven by a combination of hydrology and population—are higher.

well-being. But this metric says little about how that region or country mobilizes or uses the water that is available, or whether some needs for water can be shifted to other regions, for example, by importing food rather than growing it locally. The index also assumes that water availability is constant over time and space, but water availability fluctuates from year to year, on a seasonal basis, and regionally within countries and watersheds. Estimates of average annual water availability within the United States or China, for example, hide major differences in regional water availability (64).

## Supply/Demand Metrics

Another key liability of the population-based metric is that by focusing solely on population size and a measure of natural water availability, it has no ability to evaluate the role of water demand. In the early- to mid-1990s, several efforts to address this shortcoming led to the formulation of

**Table 3 Falkenmark water stress definitions<sup>a</sup>**

Annual renewable fresh water (m <sup>3</sup> /p/year) <sup>b</sup>	Level of water stress
> 1,700	Occasional or local water stress
1,000–1,700	Regular water stress
500–1,000	Chronic water scarcity (lack of water begins to hamper economic development and human health and well-being)
< 500	Absolute water scarcity

<sup>a</sup>Data from References 25, 59, and 60.

<sup>b</sup>m<sup>3</sup>/p/year denotes cubic meters of water per person per year.

Stockholm Environment Institute Water Resources Vulnerability Index			
Subindex	Water Use To Water Availability Ratio	Coping Capacity	Reliability Indicators
			Storage-to-flow indicator    Coefficient of variation of precipitation    Import dependence indicator
Measured variable	Ecological and socioeconomic average water-related stress	Economic and institutional ability to cope with water-related stresses	Variability of water supply

**Figure 7**

The Stockholm Environment Institute Water Resources Vulnerability Index. The Water Use to Water Availability Ratio subindex measures the average water-related stress that both ecological and socioeconomic systems place on a country's usable resources. The Coping Capacity subindex measures the economic and institutional ability of countries to cope with water-related stresses. The three indicators that make up the Reliability subindex examine the variability of water supply. Each metric is divided into no stress, low stress, stress, and high stress groups and averaged to produce an overall Water Resources Vulnerability Index score. Figure adapted with permission from Reference 27.

indices that attempted to compare supply and demand by region. In an early assessment of the vulnerability of water systems to climate change, Gleick (1990) defined a set of indicators and quantitative measures for the major river basins of the United States, including one that evaluated the ratio of consumptive water demand (D) relative to available renewable supply (Q) and identified basins as vulnerable when D/Q was 0.20 or above (65). The Stockholm Environment Institute (SEI) created a Water Resources Vulnerability Index (WRVI) that includes a similar ratio of total annual water withdrawals to annual renewable supply and classified regions as water stressed when the ratio is between 0.20 and 0.40 (66). To address the variable nature of both water availability and demand, the International Water Management Institute created an Indicator of Relative Water Scarcity in the late 1990s that included a change in water withdrawals in a country over time (calculated for 1990 and 2025) and a measure of water withdrawals as a fraction of total annual water resources. These indicators permitted an assessment of both how quickly a country's water use was growing and how close it is to natural limits (28).

### Metrics Addressing Institutional, Infrastructural, and Ecological Factors

Another refinement in the development of water scarcity indices acknowledged the role of adaptive capacity of institutions and infrastructure, the stochastic nature of hydrology, and the recognition of the role of ecological water demands. Initial efforts in these areas include the SEI's WRVI mentioned above that also tries to account for the coping capacity of societies and the reliability of water supply, including measures of natural variability, an indicator of infrastructure capacity, and a geopolitical measure of the dependence of a region on water from outside its borders (**Figure 7**) (27). A Social Water Stress Index that incorporates traditional hydrologic measures with variables from the United Nations' Human Development Index tied to access to education, political participation, and economic equity was computed for 159 countries for the year 1995 and 2025 (67) as suggestive of the ability of a region to adapt to physical water scarcity.

Another effort to integrate social, ecological, and economic measures into a measure of water scarcity was the Water Poverty Index (WPI) from the United Kingdom Centre for Ecology and Hydrology (68). The WPI is derived from a weighted average of five components measuring water resource availability, water access, institutional capacity, water use, and environmental needs (69).

**Table 4 Components of the Water Poverty Index**

Component	Definition
Resource quantity and quality	The quantity of water available, taking account of both qualitative and quantitative measures of temporal variability and water quality
Water access	A metric for the availability of water for a population including domestic and agricultural use, access to piped water supply and sanitation, time spent collecting water, and percent of water carried by women
Institutional capacity	The institutional systems in place to manage water based on educational level, health status, and access to financing, including child mortality, the percentage of households receiving wages, a pension, or other support, and membership in water users associations
Water use	The level of use of water and its contribution to the economy, including domestic and agricultural water consumption rates, livestock water use, and industrial demand
Environmental needs and impacts	The environmental impact of water management in the context of long-term ecological integrity

Table adapted from Reference 69.

Each of these components, in turn, consists of multiple variables (see **Table 4**). For example, water access includes factors for the overall availability of water, the time spent collecting water, and the percent of water carried by women. The WPI was developed both as a conventional aggregate index of different components that can be reported over time and as a gap-measure index reflecting the difference between water use in a region or country compared to the water required to meet human, ecological, and economic needs. The WPI was tested in Tanzania, Sri Lanka, South Africa, the Dominican Republic, Haiti, Guyana, and a few other countries but has not been widely adopted because of challenges with finding data and the scaling of the index from local to national or watershed levels.

### **Ecosystem Water Scarcity Metrics**

Understanding of the role of ecosystems for environmental sustainability and human health has improved in recent decades. As a result, the water community has expanded efforts to integrate ecological water needs and measures of water quality into analyses of water scarcity, allocation, and use. For ecosystems, one approach is to develop an environmental flow requirement (EFR) of rivers and wetlands and to include those requirements in scarcity assessments. The first rudimentary efforts simply assumed a fixed percentage of river runoff was needed for ecosystem purposes, but it was quickly understood that scarcity assessments should include EFRs that vary by region, season, and type of ecosystem. Pastor et al. showed for a range of local watersheds that more water was required for basic environmental purposes during drought periods (ranging from 46 to 71% of average low flows) compared to high-flow periods (17 to 45% of average wet periods) (70).

Liu et al. use this approach to assess the water scarcity in an arid river basin in Inner Mongolia, China, a basin with limited natural runoff and growing human demands for water for domestic and agricultural purposes (71). They reserve different monthly levels of river flow to satisfy the instream flow needs for healthy fish populations. For this particular river basin, they conclude that nearly one-quarter of total renewable water flows are needed to sustain healthy ecosystem conditions, increasing the risks of water scarcity for human use.

### **Virtual Water; Water Footprints; and Blue, Green, and Gray Water Scarcity**

As the discussion and analysis of water scarcity has become more sophisticated and reflective of the complexity of both the natural hydrologic cycle and different forms of human use of water, two new

**Table 5 Classification of blue water scarcity<sup>a</sup>**

Degree of shortage	Criteria
Low blue water scarcity	The blue water footprint is lower than 20% of natural runoff and does not exceed blue water availability; river runoff is unmodified or slightly modified; presumed environmental flow requirements are not violated.
Moderate blue water scarcity	The blue water footprint is between 20 and 30% of natural runoff; runoff is moderately modified; environmental flow requirements are not met.
Significant blue water scarcity	The blue water footprint is between 30 and 40% of natural runoff; runoff is significantly modified; environmental flow requirements are not met.
Severe blue water scarcity	The monthly blue water footprint exceeds 40% of natural runoff; runoff is seriously modified; environmental flow requirements are not met.

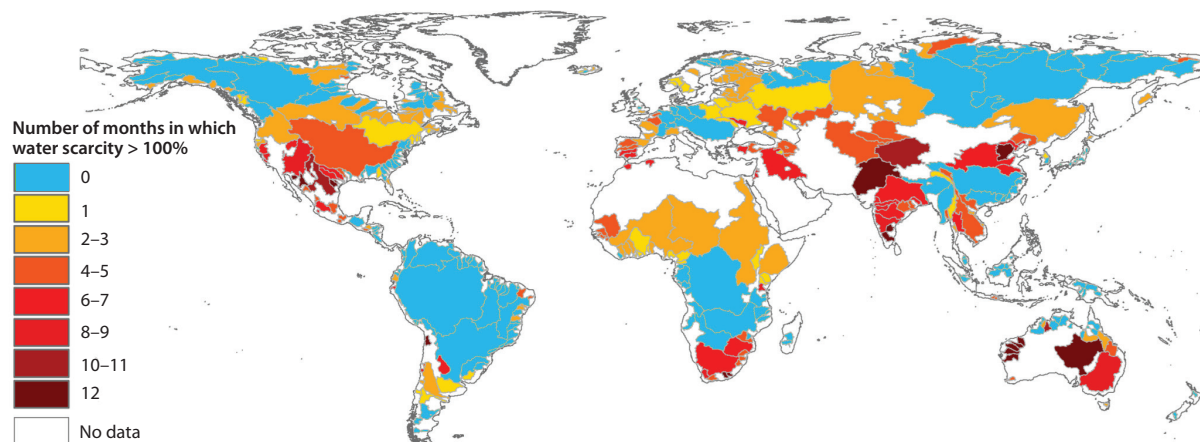
<sup>a</sup>Table adapted from Reference 77.

but related concepts have been developed to help improve water accounting and evaluate scarcity: virtual water and water footprints. These concepts improve the ability to measure water use by nations, agricultural production, and industrial goods and services and to acknowledge the role that trade and transfers of goods and services play in overcoming absolute regional water scarcity. Both concepts have been widely adopted and are used to improve the academic and practical application of water scarcity assessments.

Because water is both physically heavy and costly to transfer, economics favors transferring goods and services rather than the water itself as a way of overcoming water scarcity. Virtual water is the idea that when such products are transferred or traded, it implies the transfer or trade of the amount of virtual water required to produce those goods and services (72, 73). For example, a rough rule of thumb is that it takes approximately 1,000 tons of water to grow a ton of grain—thus transferring a ton of grain rather than 1,000 tons of water makes economic sense as a strategy for overcoming a regional shortage of water for agriculture. The water footprint—a version of the ecological footprint proposed by Wackernagel & Rees (74) that measures the natural capital requirement of a good or service—is a measure of the total water required to produce a good or service, or to support an economy, or satisfy the demands of an individual (17, 75).

As the concepts of virtual water and water footprints took hold and as researchers began to quantify the water requirements of different policies, actions, or products, a new challenge arose. Problems of freshwater scarcity have very different implications depending on the stock or flow of the water source and how it is used. When computing the annual renewable availability of fresh water, most official estimates use the sum of rainfall, available river flows, and the safe yield of groundwater. Water for agricultural production can be satisfied by rainfall or by intentional diversion of surface and groundwater flows through artificial irrigation. Water for powerplant cooling cannot use rainfall, but typically depends on river flows (or ocean water when plants are located on the coast). Pollution can make a water source unusable, reducing available supply. To address these distinctions, the concepts of blue, green, and gray water—described above—were applied (17, 76).

Blue water scarcity has been defined as the ratio of the blue water footprint in a watershed to the amount of blue water available for use after accounting for ecological flow needs (77). Green water scarcity occurs when there is insufficient rainfall to support desired uses, primarily for agricultural production. The increasing contamination of surface and groundwater resources contributes to water scarcity by making previously available water resources unusable without costly treatment. One example is the classification of blue water scarcity into four degrees of shortage: low, moderate, significant, and severe (Table 5). In this effort, Hoekstra et al. (77) found that at least 2.7 billion people are (as of 2012) living in large watersheds with severe water scarcity at least one month a



**Figure 8**

Number of months per year that the blue water footprint exceeds blue water availability for the world's major river basins, based on the period of 1996 to 2005. Blue water availability refers to natural flows of rivers and groundwater minus presumed environmental flow requirement. The blue water footprint refers to the total use of blue water for the production of goods and services in each region. Figure adapted with permission from Reference 77.

year. These kinds of metrics can also be applied regionally (78) or temporally. **Figure 8** shows the number of months that blue water demand exceeds blue water supply by region.

## Planetary Boundary Metrics

The planetary boundaries effort begun in the early twenty-first century measures how close the globe is to a set of nine thresholds. An initial assessment identifying and defining such boundaries rested on three branches of research. The first is the link between human activities and the carrying capacity of the Earth, drawing on ecological sciences and ecological economics. The second is the development of sustainability science that integrates information on essential physical, chemical, and biological processes with human actions. The third is the expanding effort to understand the dynamics of complex living systems and their resilience to stresses (79).

One of the nine boundaries underlying these indices is a measure of global freshwater use. Because the links between freshwater use and biodiversity, food production, human health, and ecological function are so strong, Rockström et al. (79) include a measure of consumptive use of blue water as a proxy for freshwater thresholds. Using this concept, they propose that physical water scarcity is reached when human withdrawals of water exceed 5,000–6,000 km<sup>3</sup>/year and that transgressing a boundary of ~4,000 km<sup>3</sup>/year of consumptive water use increases the risk of the collapse of terrestrial and aquatic ecosystems. While Rockström et al. (79) estimated that current global consumptive water use was only ~2,600 km<sup>3</sup>/year, they noted that demands were growing rapidly, especially for food production. The limitation of this approach applied to fresh water, as noted elsewhere, is that water scarcity is a regional, not global, challenge and dangerous boundary levels have already been exceeded in many places (80).

## Status of Water Scarcity Assessments

Although there are important differences and distinctions among all of the many water scarcity indicators, all of them highlight the threat of serious water problems in mid- to low-latitude regions of Africa, the Middle East, and southern Asia, driven by a combination of hydrology, rising

population levels, and weak institutional and economic capacity. In general, more recent assessments conducted with higher resolution data tend to show larger numbers of people at risk of water problems, especially in regions with large urban population densities (81). Similarly, efforts to include measures of water quality increase areas vulnerable to water scarcity by reducing the amount of water available and suitable for human use. The earlier population-based assessments suggested that between 1.5 billion and 2.5 billion people were living in areas vulnerable to water scarcity around the year 2000, but more sophisticated scarcity assessments such as the water footprint and blue-green-gray water metrics suggest that the population vulnerable to scarcity in some places and at some times could be as large as four billion (82–84).

Any discussion of water scarcity should also address, or at least attempt to define, what is meant by basic water needs—how much water, of what quality and at what price, is needed to satisfy basic human needs for water? Some efforts have been made to address these questions. When the UN declared a human right to water and sanitation in 2010, it stated, “The human right to water entitles everyone to sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic uses” (85, p. 1). The UN World Health Organization defines basic water needs to be between 50 and 100 liters (L) per day. Gleick (86) defined basic water requirements for sanitation, cooking, cleaning, and drinking to be 50 L per person per day. But additional allotments can be cited for the water required to grow food, support basic ecological functions, or produce needed goods and services, and these variables factor into whether individuals or communities perceive water scarcity to be a problem.

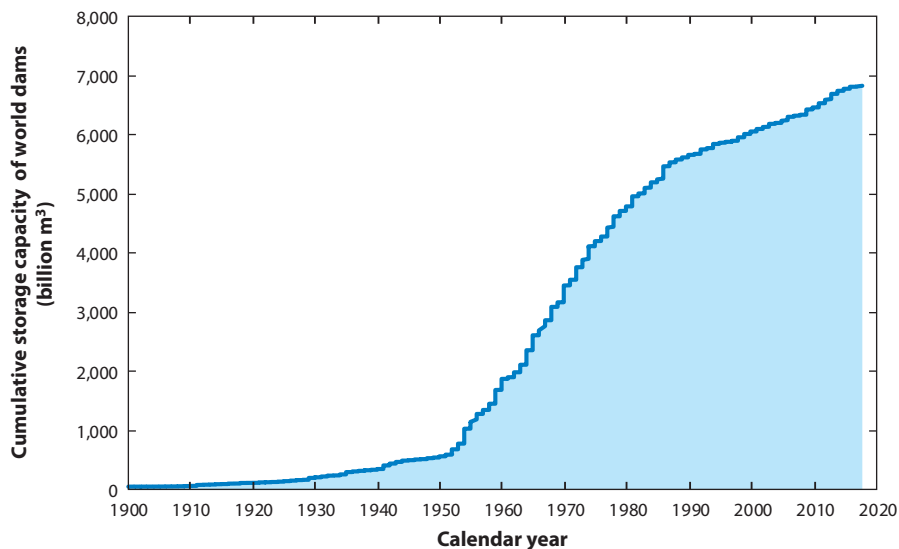
## ADDRESSING WATER SCARCITY

A key rationale for defining and measuring water scarcity is to identify effective approaches for addressing it. As our understanding of the complex factors that affect water scarcity have improved, so too have efforts to understand strategies for reducing its risks. Throughout most of the twentieth century, water planners and managers focused on addressing physical water scarcity by expanding water supply. This meant building dams and reservoirs to store water in wet periods for use in dry periods, building pipelines and aqueducts to permit the tapping of surface water supplies from evermore distant sources, and drilling wells to tap groundwater resources.

The focus on supply, however, has some important limitations that were not understood, or were ignored, in previous years. Sharma & Vairavamoorthy, for example, note that it “has led to overuse of the resources, overcapitalisation, pollution and other problems of varying severity” (87, p. 210). As supply options have become more limited, regulated, or costly, there has been a major shift in focus to rethinking how water is used, and how to use it more efficiently and productively. Demand management is increasingly acknowledged as a comparable alternative for reducing pressure on scarce water resources. In this section, we discuss opportunities for addressing water scarcity by both expanding supply and improving demand management and describe some of the tools available for realizing water management alternatives.

### Addressing Water Supply

Traditional water-supply options are still an important tool for water planners and managers, although they must be developed considering environmental impacts, the concerns of local communities, and more comprehensive cost-benefit assessments. Dams that provide water storage to mitigate flood and drought risks have provided great benefits for addressing regional scarcity, and dam construction continues around the world, although at a slower pace than in the middle of the twentieth century (**Figure 9**). The slowdown in dam construction is partly the result of growing understanding of the severe ecological damages some dams cause, more consideration of the



**Figure 9**

Cumulative storage capacity behind the world's dams, in billion cubic meters, from 1900 to 2018. Data from Reference 88.

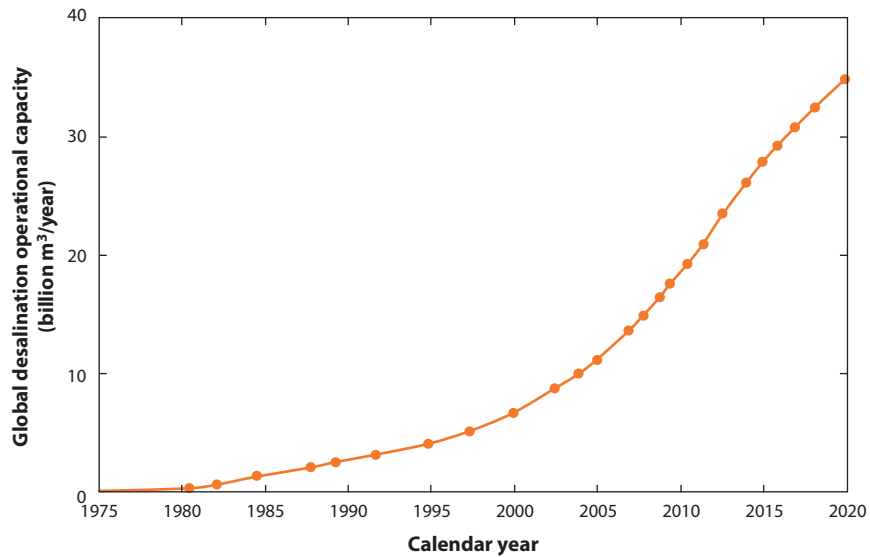
voices of local communities affected by the modification of river flows or creation of reservoirs, and fewer national subsidies for large water projects, especially in Europe, North America, and Russia. Most large dam construction today is occurring in China and Africa (88).

A substantial amount of water is still taken from traditional surface and groundwater resources, but these sources are increasingly running into peak water limits. For surface sources, once a river is fully tapped, no more water is available. For groundwater stocks, when extraction exceeds recharge, groundwater levels drop, pumping costs rise, and surface streams fed by groundwater dry up. Groundwater currently accounts for approximately a third of all water withdrawals worldwide and half or more of the water used for agricultural irrigation (89). Many major groundwater basins are already severely overdrafted, especially in arid and semiarid regions, and this nonrenewable water use is unsustainable, leading to a growing risk of water scarcity in the future (90, 91).

As the traditional water-supply options have become less feasible in many areas, there is a new emphasis on alternative water supplies, such as desalting brackish and ocean water, reusing wastewater, and capturing urban stormwater runoff. These alternatives offer the ability to expand water supplies or reuse existing sources, without taking more fresh water from natural ecosystems.

**Desalination.** Desalination technologies turn saline water from the oceans or brackish sources into a source of fresh water. Most desalination plants today use reverse-osmosis membrane filtration systems, although thermal desalination approaches are still in use. Desalination is often extremely costly and energy intensive, but it can provide new supplies for regions with no other feasible sources. **Figure 10** shows the expansion of desalination capacity worldwide between 1975 and 2020.

**Treated wastewater.** Treatment and reuse of wastewater can provide a reliable, local water supply that supplements traditional supply options and reduces vulnerability to droughts, and the quality of treated wastewater can be excellent, given modern technologies of filtration and disinfection (93, 94). It can also provide economic and environmental benefits, for example, by reducing energy



**Figure 10**

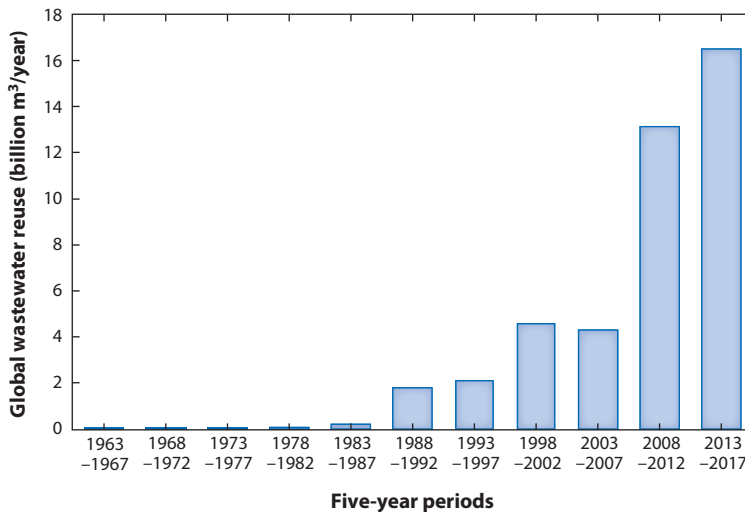
Global desalination capacity from 1975 to 2020, showing the rapid increase in installed desalination facilities. Figure adapted with permission from Reference 92.

use required to find, treat, and deliver new supplies, reducing diversions from rivers and streams, and eliminating pollution from more traditional wastewater discharges. The earliest uses of recycled water were for agriculture, although there is now a broader set of recycled water applications, including for geothermal energy production, groundwater recharge, reservoir augmentation, landscape irrigation, and industrial use. The total use of treated wastewater has increased rapidly in recent years (**Figure 11**). A handful of communities—including Windhoek, Namibia and Big Spring, Texas—practice direct potable reuse, whereby municipal wastewater is treated and put directly into the drinking water system, and such systems are expanding in both scope and acceptability (94–97).

**Stormwater capture and use.** Among the other newer sources of water is capturing, treating, and reusing urban stormwater runoff, previously considered a liability. Stormwater is now recognized to have the potential to provide substantial local quantities of water in some regions while also reducing flood risk. For example, the Los Angeles Department of Water and Power and utility partners actively capture and recharge an estimated 36 million m<sup>3</sup> of stormwater annually, along with an additional 43 million m<sup>3</sup> of stormwater infiltrating into potable groundwater aquifers through incidental recharge. Over the next 20 years, the City estimates an additional 84 million to 140 million m<sup>3</sup> per year could be captured (98). In late 2014, China launched the Sponge City Initiative to capture and reuse stormwater in 30 pilot cities. The goal of this initiative is to absorb and reuse at least 70% of rainwater in 20% of urban areas by 2020 and 80% of urban areas by 2030 (99).

## Addressing Water Demand

As supply options have become more limited, regulated, or costly, demand management is increasingly recognized as less expensive and faster to implement than water-supply augmentation and often results in important additional cobenefits, such as reduced energy demand and lower water



**Figure 11**

Global wastewater reuse capacity in billion cubic meters per year, averaged over five-year periods. The rapid growth in wastewater reuse reflects its growing value as a new source of water. Data from Reference 18.

and wastewater treatment costs (100). Water that is saved can be kept in reserve, applied toward expansion of the same use, or reallocated to other users, including the environment (101).

Improvements in the efficiency with which water is used can be achieved with a wide range of technologies and practices that provide desired benefits with less water and often less energy as well. A wide range of demand-management strategies are available for the urban and agricultural sectors, as well as for water-delivery systems. In the residential sector, for example, these include high-efficiency toilets, showerheads, washing machines, and dishwashers that can substantially reduce indoor water demands as well as drip irrigation, soil-moisture monitoring, and smart irrigation timers for outdoor landscaping. Reductions in landscape water demands can also be obtained by replacing lawns and other water-intensive plants with low water-using varieties (102).

A wide range of options are also available for improving water-use efficiency in commercial, industrial, and institutional applications. These technologies and practices have proven extremely effective at reducing the risks of water scarcity, including during droughts (103). In the agricultural sector, demand-management measures that permit farmers to grow more food with less water include precision-irrigation equipment, the use of soil-moisture and weather data to help farmers develop irrigation schedules, and remote-sensing systems for more sophisticated moisture management (104). Finally, novel technologies and management systems can detect and repair leaks in water-distribution systems, saving water while also improving the financial viability of the utility.

There are many tools available to reduce water demand, such as water and wastewater pricing, direct financial incentives, regulations, and education and outreach. Each is described in more detail.

**Water and wastewater pricing.** Well-designed tariffs can meet multiple policy objectives, including supporting the financial stability of the utility, improving affordability for low-income customers, and encouraging efficient use (105). In support of these objectives, most urban water utilities charge customers based on the volume of water provided, i.e., a volumetric tariff, in

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The “soft path for water”: an integrated set of solutions describing an alternative path for water use and management that emphasizes integrated technological, economic, and institutional approaches

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the form of uniform (the volumetric tariff is constant regardless of the quantity of water used), inclining block (the tariff increases as the quantity used increases), or declining block tariffs (the volumetric tariff decreases as the quantity increases). There is growing recognition that inclining block rates can provide financial incentives to conserve while ensuring that lower-income users are able to meet their basic water needs at a reduced cost (106).

Tariffs have been shown to be effective in improving the efficiency of agricultural water use. The Broadview Water District in California’s San Joaquin Valley implemented inclining block tariffs in 1988 to reduce the volume of contaminated drainage water flowing into the San Joaquin River. The rate was set at \$0.013 per m<sup>3</sup> for the first 90% of average water use during the 1986 to 1988 period and \$0.032 per m<sup>3</sup> for any additional water. By 1991, the district’s average water use declined by 19% due to efficiency improvements and crop shifting (107).

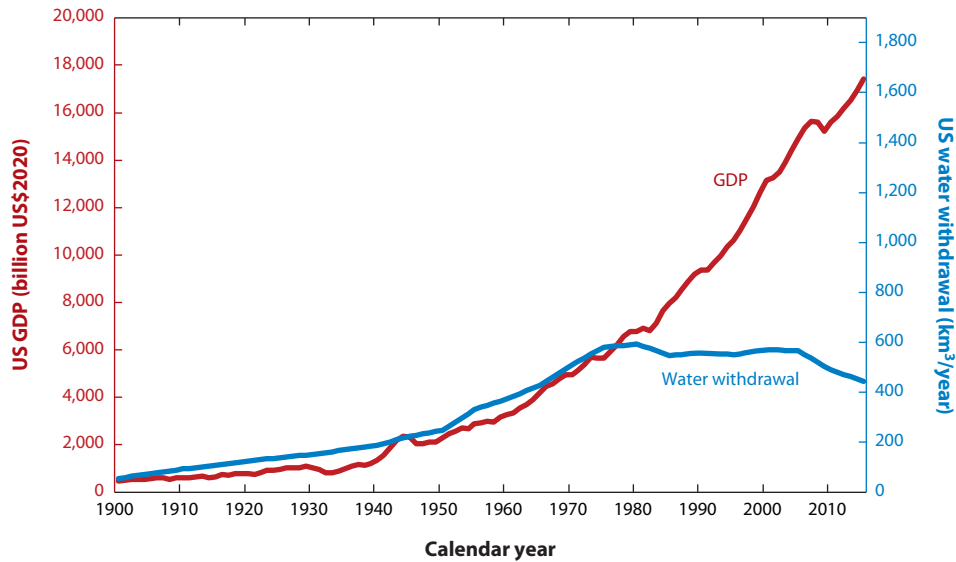
**Direct financial incentives.** Direct financial incentives can take several forms. Rebate programs are commonly used to encourage customers—including residents, business owners, and farmers—to offset the cost of purchasing water-efficient devices and replacing lawns with more efficient plants. Although these measures are often cheaper over their lifetimes due to lower water, energy, wastewater, and/or maintenance costs, water utilities may provide their customers with an incentive to defray the initial up-front cost. There are several examples of water utilities partnering with local energy utilities to augment those rebates because of the energy savings (108).

**Regulatory actions.** Regulations to improve water-use efficiency take a variety of forms. For example, the International Plumbing Code, which forms the basis for plumbing codes in several countries, specifies maximum flow rates for appliances and fixtures. Similarly, communities have limited the installation of water-intensive lawns in some arid and semiarid regions (23 C.C.R. § 490). In 2009, California passed legislation requiring urban water suppliers to reduce per capita water use by 20% by 2020, and those suppliers that failed to meet these targets were ineligible for state grants and loans. More recently, in response to drought-induced scarcity concerns, California updated this legislation, establishing water-use objectives for each water supplier based on population and local climate. Failure to meet these objectives can result in fines for the water suppliers of \$1,000 per day during nondrought years and \$10,000 per day during declared drought emergencies and certain dry years (109).

**Education and outreach.** Education and outreach programs can also be effective for promoting water conservation and efficiency. In Australia, the Water Efficiency Labeling and Standards scheme applies to seven major water-using products, requiring an easy-to-understand star rating, along with information on costs and registration. The US Environmental Protection Agency launched the WaterSense labeling program in 2006 to promote water-conserving devices that are 20% more efficient than standard products on the market and meet rigorous performance criteria. Social marketing has also gained prominence in recent years, with some programs tapping into new metering technologies and web-based platforms. For example, a recent study found that home water reports that provide customers information on their current water use and comparisons to their past use, use by similar households, and efficient use reduce water use by 5% and were especially effective in reaching the highest water users (110).

## Integrated Solutions

Because of the complexity of water systems and problems, no single supply or demand solution will be adequate to address water scarcity. In this context, the concept of the “soft path for water” as an integrated set of solutions has emerged. The term “soft energy path,” coined by Amory



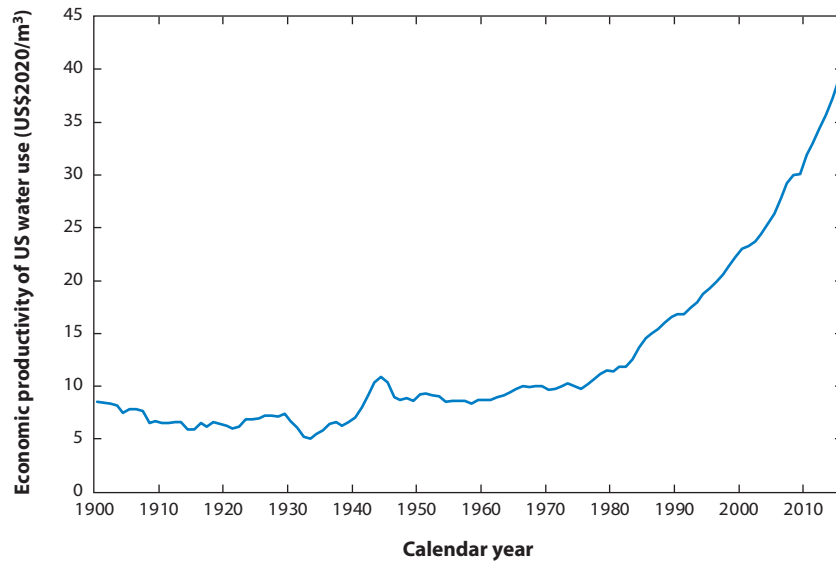
**Figure 12**

The gross domestic product (GDP) of the United States in 2020 dollars (*red line*) and total US water withdrawals in cubic kilometers per year (*blue line*) from 1900 to 2015. The figure shows the decoupling of water use from economic growth, beginning in the late 1970s. Data from References 115 and 116.

Lovins of the Rocky Mountain Institute (111), was used to describe an alternative path for energy development that emphasized integrated technological, economic, and institutional approaches to energy efficiency and smaller, decentralized energy systems fueled by renewable sources. Likewise, the soft path for water is based on similar principles, including improving the overall productivity of water use, identifying traditional or alternative and sometimes distributed new sources of water, matching water quality to users' needs, prioritizing basic human and ecosystem water needs, applying innovative economic and financing tools, and seeking meaningful local and community engagement in water management (112–114):

Soft-path planners believe that people want to satisfy demands for goods and services, such as food, fiber, and waste disposal, and may not care how much water is used—or even whether water is used at all—as long as these services are produced in convenient, cost-effective, and socially acceptable ways. Thus, society's goal should be not the use of water, but improved social and individual well-being per unit water used. (113, pp. 1526–27)

In a real-world example of how changes in water-use efficiency or productivity can reduce perceived and actual water scarcity, total water withdrawals for all purposes in the United States rose substantially during the first 75 years of the twentieth century but have been essentially flat or declining since then, despite continued growth in the economy (and population) (**Figure 12**). As a result, total economic productivity of water use, measured by dollars of GDP per unit of water withdrawn, has more than tripled from between \$6 and \$10 per cubic meter of water ( $\$/\text{m}^3$ ) withdrawal to more than \$39/ $\text{m}^3$  (in 2020\$) (**Figure 13**). These changes are the result of improvements in water-use efficiency in residential and agricultural sectors, changes in the structure of the economy, and water-quality regulations that encouraged reductions in withdrawals and increases in water reuse systems.



**Figure 13**

Economic productivity of US water withdrawals (in 2020 dollars GDP per cubic meter) from 1900 to 2015. Includes all water use. Data from References 115 and 116.

## CONCLUSIONS

Growing recognition of the importance of water worldwide and concerns about constraints on the availability of water to meet human and ecological needs are leading to new and improved understanding of water scarcity and strategies for reducing vulnerability to water shortages. A variety of concepts and indices have been developed to evaluate the risks of water scarcity and to provide more and better information to policymakers and water managers. These indicators can help raise public awareness about specific vulnerabilities, threats, and responses, but they remain imperfect tools because of limited data, differing priorities of researchers and communities, and changing conditions.

All indicators have drawbacks and limitations; no single indicator is likely to be developed that meets all needs. Part of the problem is a lack of adequate or accurate data, but a great difficulty is the complexity of water problems; their regional nature; variable hydrology; a rapidly changing climate; and differences in economic, technological, and social characteristics of communities at risk. By any measure, however, a very substantial proportion of the entire global population is at risk of some form of freshwater scarcity.

It is vital to continue to move forward even without precise definitions and quantification of water scarcity to more comprehensive and complete water solutions to ensure that basic human and ecological needs for water are met. Ultimately, the value of water scarcity assessments lies in their ability to help water planners, managers, and communities identify the most important local and community priorities and to develop sustainable strategies to meet those water needs. Looking forward, addressing water scarcity requires moving beyond a sole reliance on traditional supply-side solutions and implementing comprehensive soft-path approaches that include demand-management programs; developing alternative water supplies such as treated wastewater, stormwater, and brackish or ocean water; and improving water management and economic systems to focus on basic human needs, more realistic demand forecasting methods, and improved system reliability under increasingly extreme events.

## SUMMARY POINTS

1. Water scarcity is more than simple limitations on water availability or a mismatch between water supply and demand; it also has economic, political, social, and cultural causes.
2. Although water is abundant on Earth, disparities in the spatial and temporal distribution of water play an important role in perceptions of scarcity for humans.
3. The consequences of water scarcity include adverse impacts on human and ecosystem health; constraints on industrial and agricultural production; and a wide range of social, economic, and political disruptions, including poverty and violent conflict over access and control of water.
4. Current methods of projecting future water demands are notoriously inaccurate, relying on simple assumptions of population growth; expectations of per capita water demand; and incomplete understanding of the role of virtual water trades, water footprints, and technological advances in urban and agricultural water-use efficiency.
5. A wide range of water scarcity metrics, summarized in this article, have been developed, but no single metric can adequately represent the complexity of both drivers and risks of water scarcity. By any measure, however, very large populations are at risk of some form of freshwater scarcity.
6. Many effective approaches for addressing water scarcity have been developed and applied, but there has been a major shift in recent years from a narrow focus on supply-side solutions to more comprehensive and integrated soft path solutions that include alternative supply options, expanded water-efficiency and demand-management approaches, and more sophisticated institutional and economic policies.

## FUTURE ISSUES

1. Additional research is required to narrow uncertainties about both stocks and flows of water in the hydrologic cycle.
2. Serious gaps in data on human water use should be filled through the development and deployment of improved systematic water-accounting methods.
3. Drivers of water scarcity include demographic and economic factors, infrastructure constraints and institutional failures, and, increasingly, anthropogenic modifications of the climate that are altering hydrologic cycles. Research into the hydrologic implications of climate change has a strong base already but would benefit from improvements in modeling, regional assessments, and integration with the energy and agricultural sectors.
4. The complex role of water scarcity in worsening the consequences of poverty, and, conversely, the role of poverty in making solutions to water scarcity more difficult to implement, should be addressed by a broad community of water resource experts, social scientists, and political economists.

## DISCLOSURE STATEMENT

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