CHAPTER 1

The State of Water Resources and the Need for a Comprehensive Perspective

The Purpose of This Chapter

The role of water across sectors and societies and the evolution of its services over time have been reflected in many aspects of human life. Water, as a resource, has been studied by many disciplines. They all agree that water is unevenly distributed over time and in space, giving rise to large gaps between water needs and water availability in certain times and certain locations and stressing the need for proper demand-and-supply management. It is the reduction of the spatial and temporal gaps between supply and demand that water economics plays a crucial role in. This chapter describes the interaction between water resources and society over time in various parts of the world, the effects of climate change on the available water supplies, the technological means available to cope with water scarcity and deteriorated quality, the institutional and legal means experienced by various countries, and the types of decisions needed to implement and manage such means.

1.1 Background

Water is a natural resource with flow and stock dimensions and with several origins.[1] Most water is natural, resulting from precipitation (rain and snow) that flows in rivers, and is stored in lakes and groundwater aquifers. Some aquifers are replenishable (from precipitation) and some are fossil, being stored a long time ago (thousands of years) in deep aquifers

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[1] We would like to acknowledge the research assistance of Vincent Ta, allowing us to present the various trends, both inter-temporal and cross-sectional, of the various variables presented in this chapter. We benefited from access to data and maps that were produced upon our request by Dr. Amir AghaKouchak and Dr. Phu Dinh Nguyen, Center for Hydrometeorology & Remote Sensing, University of California, Irvine; Dr. Manzoor Qadir, Institute for Water, Environment and Health, United Nations University, Ontario, Canada; Dr. Naota Hanasaki, National Institute for Environmental Studies, Japan; and Dr. Sarah Wheeler, University of South Wales, Adelaide, Australia.

that are either nonrenewable or very slowly recharged. Some water can be produced by recycling treated wastewater or by desalinating seawater or brackish (saline) sources. More on the various types of water will be discussed in Chapter 2. Hereafter, unless otherwise noted, we will refer to natural water as renewable.

1.2 Spatial and Temporal Water Availability: How Much Water Is There and How Is It Used?

Existing data on renewable natural water availability worldwide have expanded over time with the introduction of satellite technologies and computational power. Several studies present estimates of the global renewable water supplies (Shiklomanov, 1993, 1996, 1999, 2000; Clarke and King, 2004). These data suggest that annual flow of water available for sustainable extraction (without drawing down stocks or leading to contamination) is more or less constant, as can be seen in Table 1.1, which refers to global and continental available renewable natural water (ARNW) resources.

Against the more or less fixed quantity of ARNW, it is interesting to follow the changes in annual global withdrawals between 1900 and 1995, and forecasts (performed in 2000) for 2000, 2010, and 2025, as can be seen in Figure 1.1.

The ARNW resources are used by households for drinking, cooking, washing, and outdoor uses; for agricultural production (crop irrigation,

Table 1.1 *Available renewable natural continental and world water resources*

	Available renewable natural water resources (km^3/year)		
Continent	Mean	Min.	Max
Europe	2,900	2,254	3,410
North America	7,980	6,895	8,917
Africa	4,050	3,073	5,082
Asia	13,510	11,800	15,008
South America	12,030	10,320	14,350
Australia and Oceania	2,400	1,891	2,880
World	42,780	39,780	44,750

Note: Table elaborated by authors. Min. and Max columns represent possible changes in available renewable natural water resources as a consequence of wet and dry years. One cubic kilometer (km^3) is equivalent to 1 billion cubic meters (m^3) or 810,714 acre-feet.
Source: Based on data in Shiklomanov, 2000

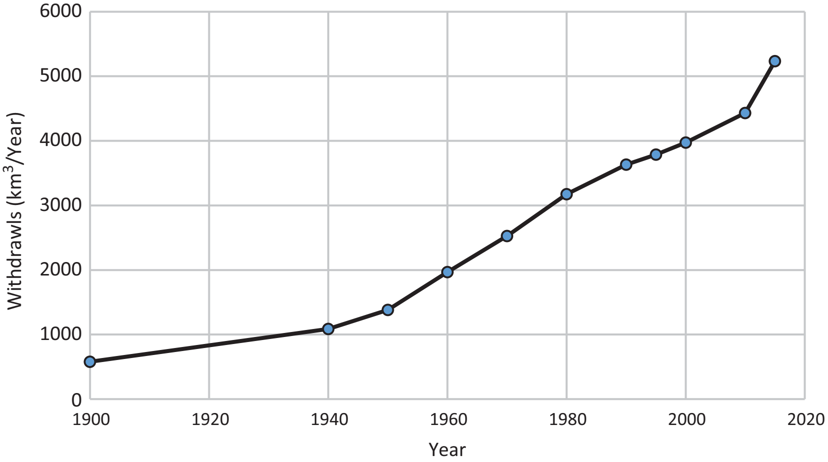

Figure 1.1 Estimates and forecasts of global water withdrawals between 1900 and 2015 (km^3/year).
Source: Adapted from data in Shiklomanov (2000)

livestock and aquaculture); for industrial production; and for environmental purposes. Water is also used in cooling, mining, and navigation, although to a lesser extent. Some uses (household, irrigation, industrial production, mining) are called consumptive because a part of the water consumed is no longer available in the same year for other uses, either because it disappears or moves away from its original consumption location, or because its quality is no longer adequate for use. Other uses are non-consumptive, although they may change the nature and timing of water availability (navigation, cooling, hydropower, and in-stream use for environmental purposes). A bulk estimate (UN-Water, 2015) suggests that 70, 20, and 10% of the available water flow are consumed in irrigation, industrial, and urban uses, respectively. It should be noted that with the introduction of improved wastewater treatment technologies, household and industrial sewage can be treated and be reused for irrigation, cooling, environmental purposes, and, in some cases, household purposes (e.g., in Orange County, California).

1.3 Population Trends and Available Renewable Natural Water Resources

Water is necessary for subsistence (drinking, cooking, hygiene), for agricultural and industrial production, and for environmental purposes.[2] It is therefore of interest knowing how much water is available in different locations intra- (within a year) and inter-temporal. Even if water is abundant, its quality may restrict its use, e.g., saline water is not suitable for drinking or irrigation of certain crops without proper treatment.

The availability of water for human consumption represents its level of scarcity. There are several measures for water scarcity (Brown and Matlock, 2011), but we will use one crude measure that addresses only the available quantity. Available water quantity per capita is calculated by dividing the total renewable natural water available in a sustainable fashion (which on average is fixed at the levels indicated in Table 1.1) by the population at a given year in the location of interest (world, continent, country, region, river basin). We calculate the scarcity index for all-natural water sources (rivers, lakes, aquifers) as well as for subsets of the water resources, such as groundwater. Figures 1.2 and 1.3 demonstrate the change in the water availability index during 1945–2015.

To allow reference to scarcity levels, we use the "scarcity categories" suggested by Falkenmark (1989) and coined as the "Falkenmark indicator," which is broadly used in the literature. The Falkenmark indicator proposes three levels of available renewable water per capita per year, measured in cubic meter per capita per year and denoted CMpy, as follows: CMpy above 1,700 indicates No Stress, CMpy between 1,000 and 1,700 indicates Stress, CMpy between 500 and 1,000 indicates Scarcity, and CMpy below 500 indicates Absolute Scarcity.

As can be seen from Figures 1.2 and 1.3, water availability per capita at year t, calculated as $CMpy_t = \frac{W}{Pop_t}$, with W being the average (fixed) available renewable water resources and Pop_t being the population at year t, takes, for most regions, a declining hyperbolic trend over time. The forecasted population growth trends for 2050 and beyond are negative for some countries. This is reflected in an inclining part of the available renewable water resources per capita per year graph.

In Figures 1.2 and 1.3 we draw the Falkenmark indices of 1,700, 1,000, and 500 m^3/person/year. We expect that these lines will be intercepted by the water availability per capita lines earlier in time for countries with higher levels of water scarcity and later in time for more water-abundant countries.

Another way to measure scarcity is by referring to the parameters of the water availability per capita graphs (in Figure 1.3, for example). We

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[2] From hereafter we will use the term "water" instead of "water resources."

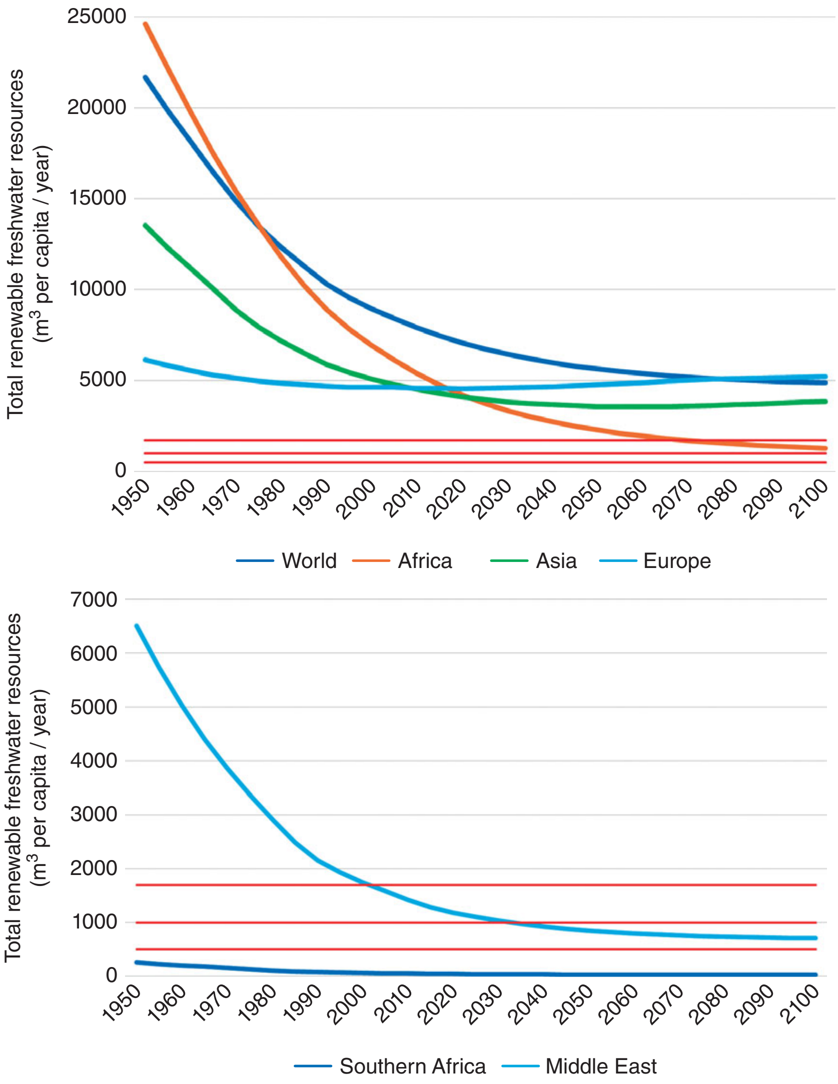

Figure 1.2 Freshwater resources per capita by continent (1) and by representative water-scarce regions (2) (1950–2015).

Note: Population values beyond 2015 are based on mid-level forecasts; the horizontal red lines in Figures 1.2 and 1.3 represent, from top to bottom, the Falkenmark water availability levels of 1,700, 1,000, and 500 m^3/person/year, which, respectively, indicate Stress, Scarcity, and Absolute Scarcity.

Source: World Data FAO AQUASTAT and Population Data from United Nations, Department of Economic and Social Affairs, Population Division (2015)

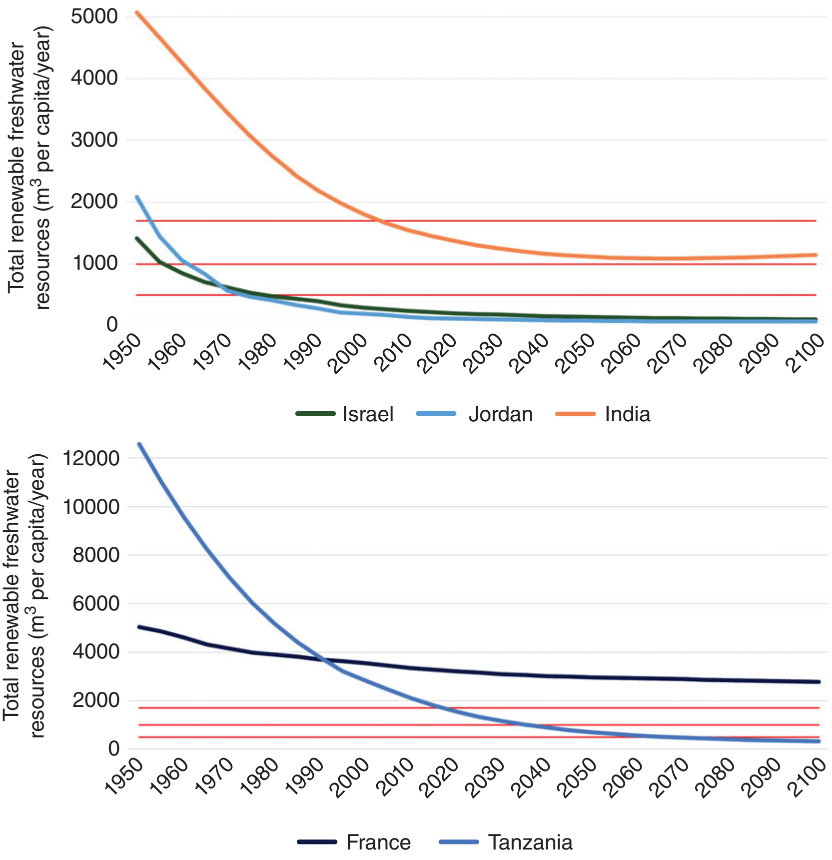

Figure 1.3 Freshwater resources per capita for a sample of water-scarce (1) and water-abundant (2) countries (1950–2015).
Source: World Data FAO AQUASTAT and Population Data from United Nations, Department of Economic and Social Affairs, Population Division (2015)

can compare the $MCpy_t$ curves to declining linear trend, $Y - \vartheta t$ with intercept Y and slope $-\vartheta$. As can be depicted from the sample graphs, some regions (continents, countries, or even subregions within a country – not presented) can be identified by these two parameters: the intercept and slope of the water availability per capita trend. The intercept represents the fixed water endowments per capita of that region and the slope represents the population growth rate in the region (if we can measure the water quality degradation, this slope can also represent the water scarcity due to deteriorating quality). The lower the intercept the more severe the scarcity, and the higher the slope the faster water becomes scarce in that region.

Another important observation is that while continental water-scarcity trends (Figure 1.2) suggest “No Scarcity” in most continents, and “Stress” toward the year 2050 in most continents, the situation still varies dramatically across countries in these continents (see Figure 1.3 for selected countries with extreme water-scarcity conditions).

So far, we have discussed water-scarcity trends associated with population growth, given that on average the available natural renewable water resources are fixed. Climate change will most likely affect the average supply of natural water unfavorably in many regions, particularly in arid and semiarid regions, thereby exacerbating water scarcity in these regions.

1.3.1 Additional Trends Affecting Water Scarcity

In addition to the population trends described above, there are several additional trends that affect spatial water scarcity. We will discuss here one trend – the increase in urban population – that affects local water scarcity, the economics of investment in water infrastructure, and also the opportunity to create new sources of water (manufactured/produced water).

Urban population growth is affected by many factors, including international migration and rural-to-urban migration, both of which are affected by water scarcity; poor environmental conditions; social unrest (civil wars) at the migration source region; and high natural population growth rates. The urban population in 2014 accounted for nearly 55% of the total global population, up from one-third in 1960. Such increase in urban population added about 2.5 billion people to cities over the past 55 years. This trend is still ongoing: the annual growth rate of urban population is predicted to be 1.84%, 1.63%, and 1.44% during the periods 2015–2020, 2020–2025, and 2025–2030, respectively (UN-DESA-PD, 2015). Figures 1.4 and 1.5 present the situation of urban population in 1975 and 2015.

The urban expansion between 1975 and 2015 is significant as can be seen from the two previous figures. In 1975, there were 11 urban centers with 10–15 million inhabitants, 1 urban center with 15–19 million inhabitants, and 2 urban centers with 20–24 million inhabitants. In 2015, the corresponding numbers were 23, 5, and 10, with 2 urban centers containing above 30 million inhabitants. The economic implications are enormous. First, such changes mean that the increased urban demand for

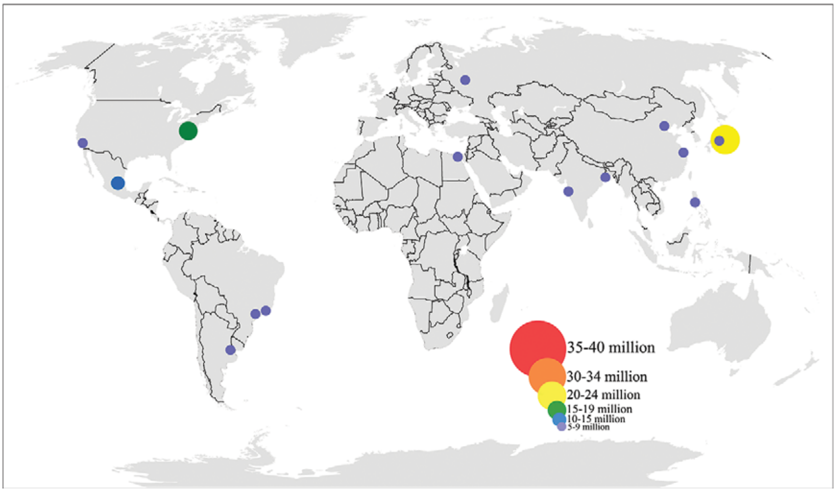

Figure 1.4 Major world cities with populations exceeding 5 million inhabitants in 1975.
Source: Authors' elaboration using data from United Nations, Department of Economic and Social Affairs, 2006

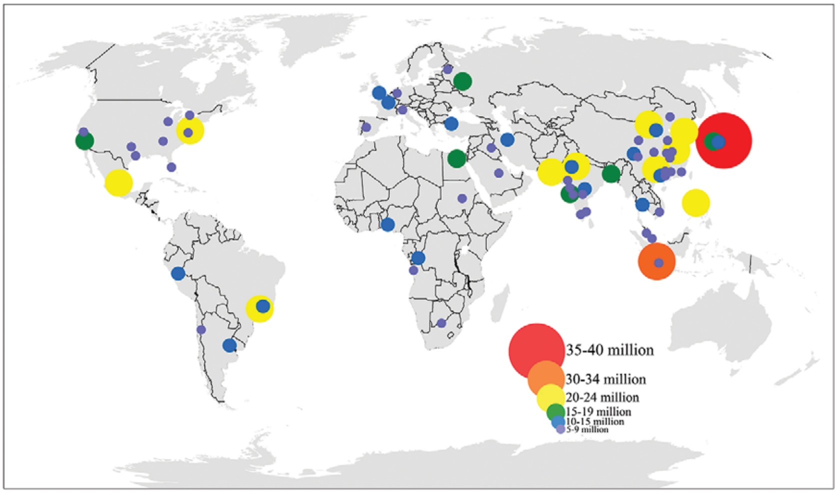

Figure 1.5 Major world cities with populations exceeding 5 million inhabitants in 2015.
Source: Authors' elaboration, using data from Demographia World Urban Areas, 11th Annual Edition, 2016

water needs to be addressed by new reservoirs and conveyance systems, which translates into major long-term investments in infrastructure. Second, as indicated by UN-DESA-PD (2015) and as can be seen in Figures 1.4 and 1.5, most of the urban growth is and will be in developing countries (mainly Asia), suggesting a significant burden on the budgets of these economies for investing in water supply and sanitation infrastructure (support for such investments as well as for prevention of waterborne-disease outbreaks are often sought from the donor community). Third, and on the positive side, this situation, if handled well and supported by appropriate funding institutions and regulations, could create an opportunity for new water sources in the form of treated wastewater that can be recycled and reused in irrigated agriculture, thus releasing freshwater for urban use (Hernandez-Sancho et al., 2015; Tsur, 2015). We will discuss this opportunity in Section 1.9.

1.4 Climate Change Shock Effects on the Water System

Climate change has been affecting our natural systems and the economy for quite some time. Impact of climate change on the water system will be felt in several ways. First, a change in average precipitation: Some locations face a reduction while others face an increase (Figure 1.8). The second impact has been felt through increase in variability of the precipitation events, ranging from increased number of drought and flood events and increased duration and severity of these events. Another effect climate change has had on the water sector is increased evaporation due to higher temperatures, leading to less effective irrigation in most parts of the world (Figure 1.8). A comprehensive discussion of the information in Figure 1.8 appears below. But before this, we would like to focus on drought and flood event distribution over time.

The Center for Natural Disaster suggests a sharp increase in drought and flooding events around the world in the past 100 years, with increased longevity and severity (Gupta-Sapir et al., 2003). Figures 1.6 and 1.7 present a sharp increase in the number of drought and flood events, respectively, since the 1960s.[3] These extreme events have significant economic impact that, if incorporated into the policy realm of the various drought- and flood-prone countries, would change economic considerations within the water sector.

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[3] It is also possible that the upward trend reflects increase in reporting and recording capacity over time.

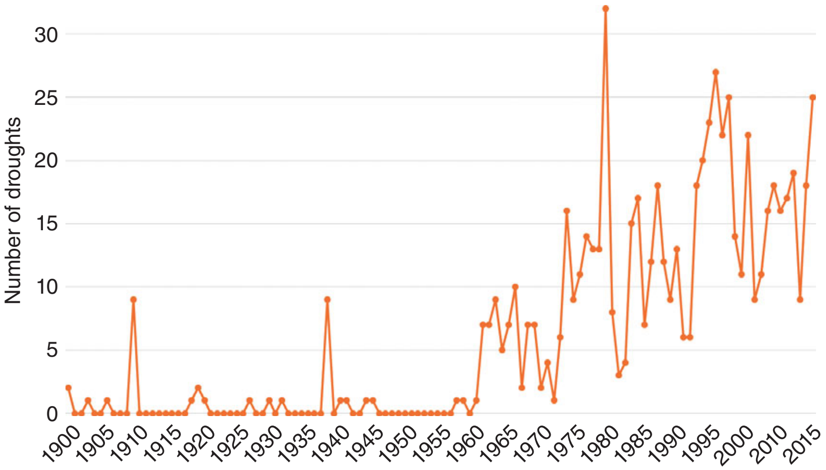

Figure 1.6 Global drought events between 1900 and 2015.
Source: D. Guha-Sapir, R. Below, Ph. Hoyois – EM-DAT: The CRED/OFDA International Disaster Database – www.emdat.be – Université Catholique de Louvain – Brussels – Belgium. [Permission granted on EM-DAT website]

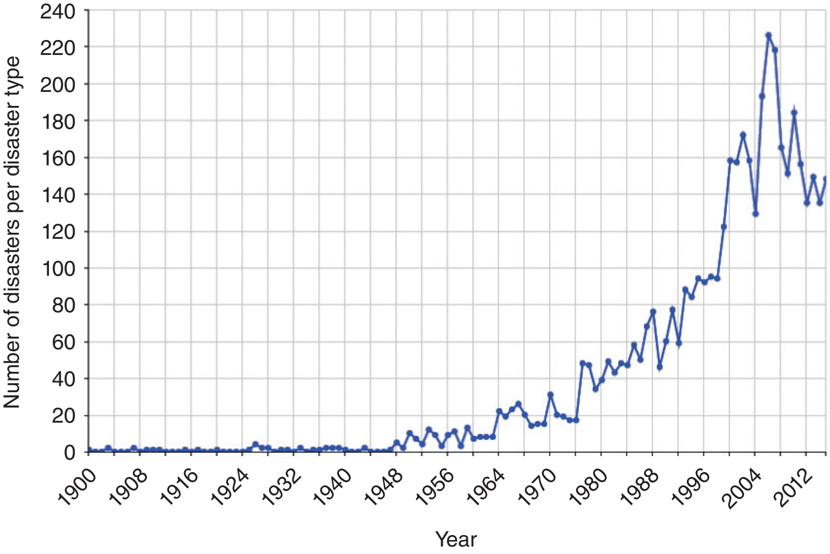

Figure 1.7 Global flood events between 1900 and 2015.
Source: D. Guha-Sapir, R. Below, Ph. Hoyois – EM-DAT: The CRED/OFDA International Disaster Database – www.emdat.be – Université Catholique de Louvain – Brussels – Belgium. [Permission granted on EM-DAT website]

Table 1.2 *Number of drought and flood events between 1900 and 2015 divided into three periods*

Decadal period	Total drought events	Total flood events
1900–1938	20	30
1939–1976	90	383
1977–2015	578	4,152

Source: Data in Figures 1.6 and 1.7

A comparison of the aggregated number of drought and flood events over the past century (Table 1.2) suggests a remarkable increase in the number of these events over the past 40 years compared to the period during the first eight decades of the twentieth century.

With such increases in extreme flood and drought events during 1900–2015, what would the future be with climate change's expected impacts? The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Stocker et al., 2013) suggests a range of future values of hydrological variables that demonstrates expected effects of climate change on the hydrological cycle. Figure 1.8 presents predicted annual mean values of six hydrological variables during the period 2081–2100, including precipitation, evaporation, relative humidity, evapotranspiration, runoff in rivers, and soil moisture.

The six variables listed in Figure 1.8 demonstrate a distributional range of both increase and decrease in precipitation (−0.8 to +0.8) millimeters per day, evaporation (−1 to +0.8) millimeters per day, relative humidity (−9 to +6%), evapotranspiration (−0.8 to +0.8) millimeters per day, runoff (−40 to +40%), and soil moisture (−10 to +10%), suggesting a wide range of variability across different parts of the world.

Watching the changes in precipitation in two of the focus points in our book – California and the Jordan River Basin[4] (Figures 1.9 and 1.10, respectively) – it is clear that these two semiarid regions face a major decline in precipitation as well as increase in their variability. These trends are consistent across many regions and may differ only in magnitude.

[4] Including Jordan, Israel, the Palestinian Authority, and parts of southern Lebanon and southwest Syria.

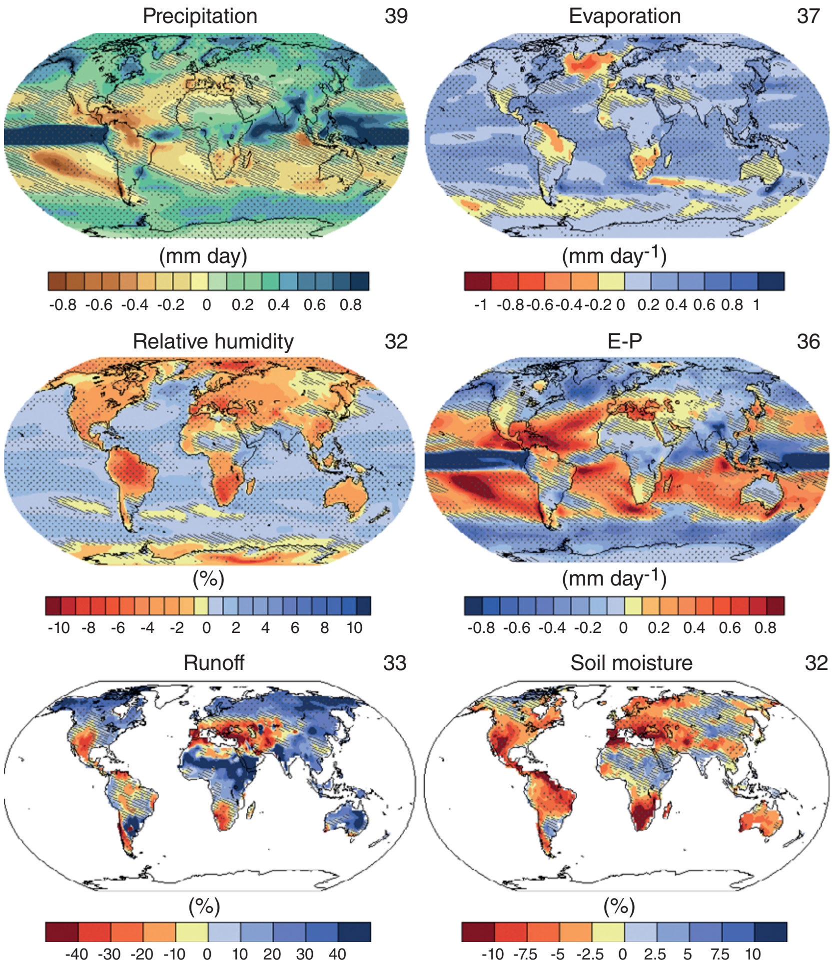

Figure 1.8 Future changes in six main hydrological parameters predicted for 2081–2100. Source: Adapted from the IPCC WGI AR5 (figure TFE.1, fig. 3), Stocker et al., 2013 [Permission obtained]

What do we learn so far from the past trends of hydrological parameters and predicted future changes? The data available so far suggest that water becomes scarcer (both in terms of quantity, quality, and variability) and that the level of scarcity varies by region. Why is that important for the analysis in our book? Because this means that economic and policy decisions are required in order to deal with scarcity. It also means that economic policies vary among locations, based on severity of scarcity.

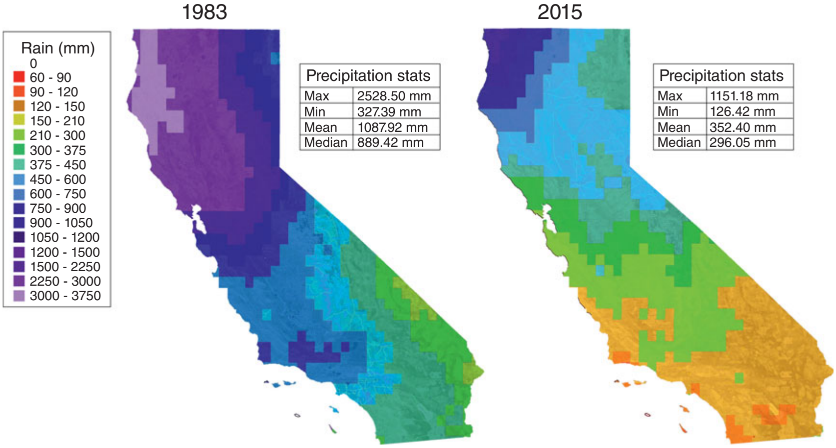

Figure 1.9 Annual precipitation in California, 1983 and 2015.
Source: Modified by authors from data provided by Center for Hydrometeorology and Remote Sensing at the University of California, Irvine, http://chrs.web.uci.edu/

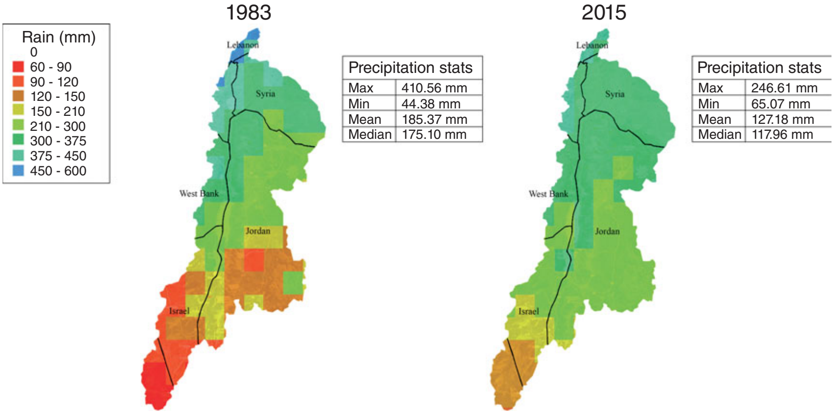

Figure 1.10 Annual precipitation in the Jordan Basin States, 1983 and 2015.
Source: Modified by authors from data provided by Center for Hydrometeorology and Remote Sensing at the University of California, Irvine, http://chrs.web.uci.edu/

1.5 Other Human-Made Shocks to the Water System

While climate change effects on the water cycle are also the results of human-attributed impacts that increase global greenhouse gas (GHG) emission, this is not the only shock caused to the water system by anthropogenic activities. Climate change–induced impacts are global in nature, meaning that GHG emission in any location contributes to GHG concentration in the atmosphere, which then affects different regions with different extents.

Other human-made shocks are more local in nature. We will refer only to a couple of impacts, translating into lower groundwater (GW) level in aquifers that makes water pumping more expensive, and to deteriorated water quality that makes the water unsuitable for consumption for various purposes. Over-pumping of groundwater leads also to land subsidence, which, depending on the geology/morphology of the aquifer, can be associated with significant economic damage. We do not address the economics of land subsidence in this book.

Renewable groundwater resources comprise nearly 31% of the renewable freshwater resources on earth (Shiklomanov, 2000). As such, the sustainable yield of groundwater (that does not draw stocks below certain thresholds) is an important and valuable resource that in some semiarid regions, e.g., the Middle East and western United States, is the major source of water for irrigation and urban use.

Moreover, groundwater stocks serve as a buffer to smooth water supply during dry years, when surface water becomes less available. In addition, due to poor regulation and malfunctioning institutions for groundwater pumping in many countries, this resource has always been used beyond its safe recharge, mainly due to expansion of irrigation areas. This trend has resulted in lowering of the water table level, land subsidence, and deterioration of water quality due to intrusion of saltwater and deep percolation of pollutants from irrigated fields. For example, according to Shah (2009: figure 2.1), between the years 1940 and 2009, India, China, and Mexico increased groundwater extraction from 10 to 260, from 10 to 90, and from 20 to 60 km^3/year, respectively. These countries, and many others, face both depleted and contaminated aquifers and the meager consequences to the people that rely on this resource in the form of congestion cost, saline water intrusion from adjacent aquifers, and seawater intrusion (Shah, 2009; CONAGWA, 2010; Shen, 2015). Figure 1.11 presents recent results from a study that documented trends in the depletion over time of several major aquifers around the world and its extent.

Data in Figure 1.11 suggest that of the 37 major aquifers studied, 23 face 10–20% depletion. While not all world aquifers were included in the study, the results are the mirror image of the situation in most of the groundwater aquifers around the world. Such depletion has remarkable

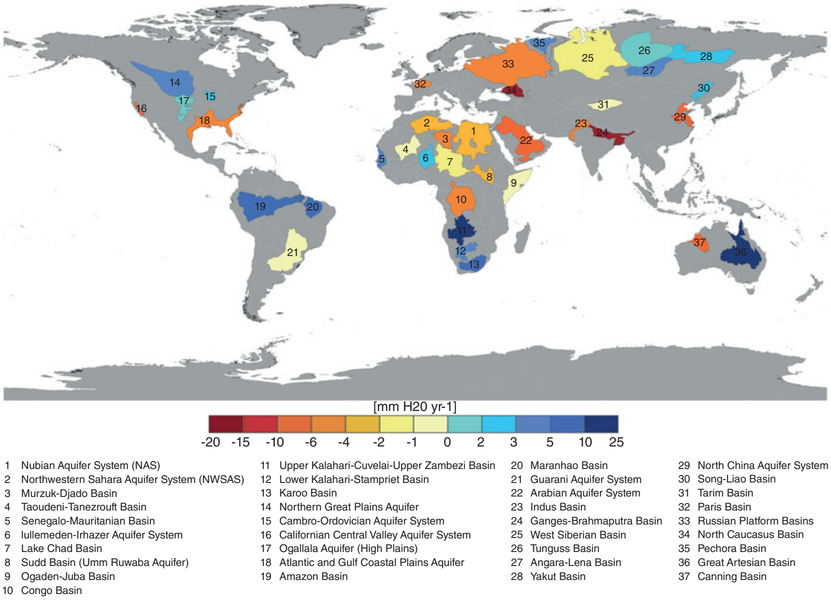

Figure 1.11 Trends in groundwater levels in major aquifers.
Source: Richey et al. (2015), Quantifying Renewable Groundwater Stress with GRACE, Water Resources Research, doi: 10.1002/2015WR017349 [Permission obtained]

impacts on the ability of GW stocks to play their role as buffers in periods of severe scarcity. Another aspect of such depletion is the effect of water-level drawback on the water quality in the aquifers due to the intrusion of seawater, where applicable. And finally, depletion of water level in aquifers leads to an increase in the pumping cost, which makes irrigated agriculture to be less profitable.

Richey et al. (2015) developed a groundwater depletion index, called RGS (Renewable Groundwater Stress), based on water withdrawal above natural recharge. Using GRACE observations for the period 2003–2013, the authors calculated RGS values for the world's 37 largest aquifers and classified the groundwater stress conditions of each aquifer as low, moderate, high, or extreme. Aquifers with high or extreme stress conditions undergo depletion at alarming rates, which means that their exploitation has been, or soon will be, limited due to vanishing water stocks or quality deterioration triggered by the declining water head. Of the 37 major aquifers, Richey et al. (2015: table 3) identified 12 to be under high or extreme stress, including the Great Plains and Ogallala aquifers in North

America, the Indus Basin and Tarim Basin aquifers in India and China, 6 aquifers in Africa, and the Great Artesian Basin aquifer in Australia. Konikow (2013) uses data on groundwater withdrawal and natural recharge during the period 1900–2008 to estimate groundwater depletion for all major US aquifers. Aggregate groundwater depletion (extraction above recharge) in 2008 was 25 Km^3, which amounts to 70% of total US domestic water consumption during that year.

Water quality deterioration around the world is another major constraint on use of water and is directly and indirectly associated with the high economic cost of waterborne diseases and their prevention. Water pollution, resulting from economic activities, indicates a failure of institutions and regulatory interventions to curb such pollution. The major water pollution sources are human activities: residential, industrial, and agricultural. The data are staggering (UN-Water, 2013): about 80% of the residential sewage in developing countries is discharged untreated to natural water bodies, and the industrial sector globally release between 300–400 million tons of raw sewage to water bodies. Agriculture pollutes groundwater and soil with nitrates (from fertilizers) and minerals (salinity). Such pollution reduces the suitability, hence availability, of groundwater for irrigation and drinking purposes. In addition, salinization of soils reduces the productivity of agricultural land and, in addition, increases the volume of water needed to flash the pollutants from the soil profile (Assoulin et al., 2015).

1.6 The Gap between the Supply and Demand

With increased population-driven demand for water, on the one hand, and the climate change–driven shocks to the water system, on the other hand, the gap between water needs and natural water supply has been widening over time. A recent study (The 2030 Water Resource Group, 2009) estimates that conventional approaches will not be sufficient to close this gap in the near future. Indeed, the cited study considers mainly structural approaches, namely, infrastructure and special linking of water sources (including intra- and inter-basin water transfers), which are extremely costly. Based on the analysis in The 2030 Water Resources Group (2009: 45–48), under a number of simplifying assumptions, the global water consumption (for all purposes) is currently 7,000 Km^3. About 20% of this quantity could be provided by increase in quantity supplied under business-as-usual investments and improvements. An additional 20% of this quantity will be provided by improvements in water productivity in agriculture and industrial production. The remaining 60% is a gap that will need to be addressed by means beyond those considered under business-as-usual (or conventional) approaches. In Section 1.7, we discuss the various measures, both structural and non-structural that could be considered to close the gap between water needs and available water supply.

1.7 Technological Means to Close the Gap (Supply Management)

The gap between demand and supply, as defined earlier, can be reduced by increasing the supply of water. Supply of water can be increased by regulating floods, snowmelt, and river flow; by recycling water; and by producing new water via desalination. Each of these ways to close the gap between supply and demand has an opportunity cost associated with the benefits of increased supply.

1.7.1 Reservoirs

Building new reservoirs increases the storage capacity for water as can be seen in Figure 1.12. It is striking that most of the reservoirs around the world are located where water is abundant (such as South America and Southeast Asia) or in countries with financial means (such as the United

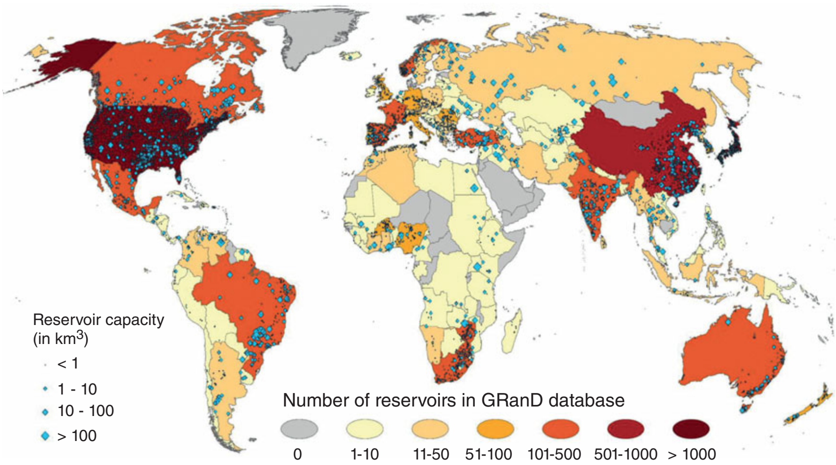

Figure 1.12 Water reservoirs around the world (2011).
Source: www.sciencedaily.com/releases/2011/06/110602102447.htm

States and Western Europe) suggesting that such an approach to closing the gap is not effective in semiarid and arid regions where the gap is significant.

1.7.2 Wastewater Treatment and Reuse

Treating and reusing municipal wastewater is an untapped source of water that has a tremendous potential, especially with the major increase in urban population (Hernandez-Sancho et al., 2015; Tsur, 2015). Reuse of residential wastewater for irrigation purposes, if done properly, achieves two objectives. First, it releases freshwater that can be used for residential consumption, and second, it prevents the pollution of the environment. Figure 1.13 presents the ratio of treated wastewater to produced sewage in counties around the world. As can be seen, most countries in 2012 and especially the developing countries have ratios in the range of 0–40%.

In addition to Figure 1.13, which shows relative values of treatment to production of wastewater, Table 1.3 provides the number of wastewater facilities and the global total wastewater treatment capacity during the periods 1990–1997 and 1998–2013. Values in Table 1.3 suggest that the rise is significant: a 398% increase in the number of wastewater treatment facilities worldwide and a 20% increase in the global capacity. Both

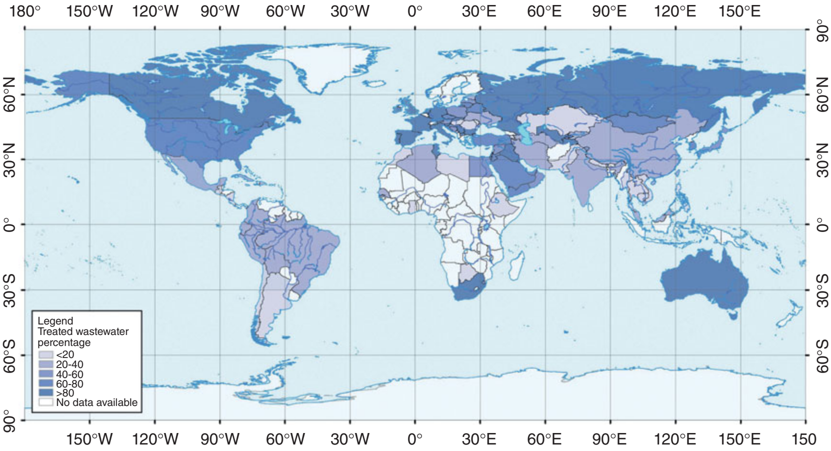

Figure 1.13 Ratio of treated wastewater to produced sewage in selected countries (in 2012).
Source: Sato et al. (2013) [Permission obtained]

Table 1.3 *Global number of wastewater facilities and capacity (billion cubic meters per year)*

Period	Global number of facilities	Global capacity (10^9 m^3/year)
1990–1998	18,062	255,524.1
1999–2013	72,007	306,873.4

Source: FAO AQUASTAT

indicators are impressive. They mean also that during the period 1999–2013, the additional treatment facilities added to the stock were mainly local and small.

Awareness of the need to treat residential sewage doesn't mean that treated wastewater will be applied only for irrigation. So far, treated wastewater is used for various purposes, including irrigation of agricultural crops, but also irrigation of golf courses, irrigation of public areas in urban centers, support for ecosystem services (e.g., Albufera wetland in southeastern Spain – see Andreu et al., 2013), and for recharge of groundwater aquifers, which can contribute to irrigation and residential water supply following additional treatment (4 Southern California, 2016; Orange County Sanitation District, 2016). Table 1.4 presents trends of treated wastewater reuse in California between 2001 and 2015. The use of recycled water for irrigation in Israel has more than doubled during the past 20 years and Israeli irrigators now use more recycled water than fresh (natural) water (see discussion in Chapter 2).

1.7.3 Irrigation Expansion and Improvements

The increased demand for food due to higher world population levels and changes to their diet and income means that more water will be needed for food production in many parts of the world. A look at historical data on area equipped for irrigation can provide some insights (FAO, 2016). Globally, the area equipped for irrigation increased from 164 to 324 million hectares (ha) over the past 50 years. Some countries facing severe water scarcity led such increases. For example, significant percentage increases occurred in Saudi Arabia (from 0.3 to 1.6 million ha), Libya (from 0.1 to 0.5 million ha), Yemen (from 0.2 to 0.7 million ha), China (from 45 to 68 million ha), and India (from 26 to 67 million ha).

Table 1.4 *Treated wastewater reuse for various purposes in California, 2001, 2009, 2015*

Year	2001		2009		2015	
Beneficial reuse	Acre-feet/year (rounded values)	Percent total	Acre-feet/year (rounded values)	Percent total	Acre-feet/year (rounded values)	Percent total
Golf course irrigation	115,000	22	44,000	7	56,000	8
Landscape irrigation			112,000	17	126,000	18
Agriculture irrigation	239,000	45	245,000	37	219,000	31
Commercial	22,000	4	6,000	1	5,000	1
Industrial			50,000	7	67,000	9
Geothermal energy production	1,000	≪1	15,000	2	18,000	3
Seawater intrusion barrier	22,000	4	49,000	7	54,000	8
Groundwater recharge	49,000	9	80,000	12	115,000	16
Recreational impoundment	35,000	7	26,000	4	28,000	4
Natural systems: restoration, wetlands, wildlife habitat	22,000	4	30,000	4	24,000	3
Other (sewer flushing, misc. wash-down etc.)	20,000	4	12,000	2	2,000	≪1
Grand total	**525,000**		**669,000**		**714,000**	

Source: Dinar et al., 2018 (Adapted from California State Water Resources Control Board [n.d.])

1.7.4 Desalination

The last resort is the investment in desalination. While expensive, desalination guarantees a stable supply of water, mainly for urban and industrial uses, but in some countries (mostly in the Middle East) also for irrigation. Figures 1.14 and 1.15 provide information on the expansion of the

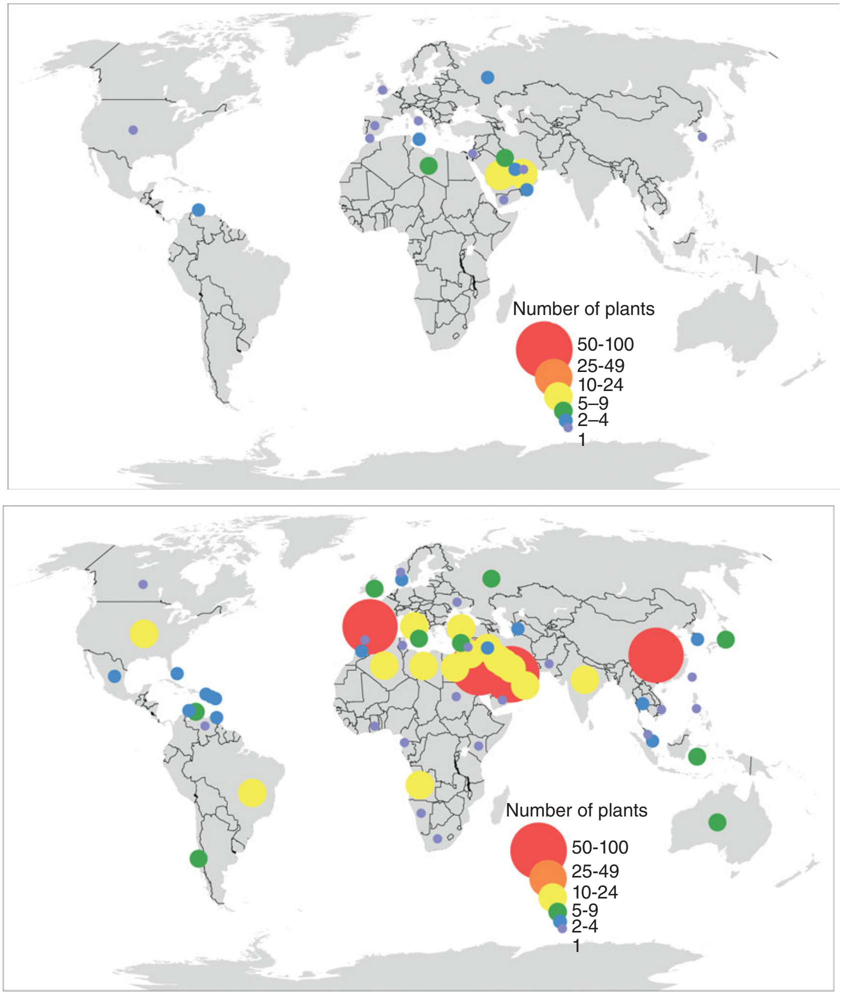

Figure 1.14 Number and location of desalination plants in 1990 (top) and 2014 (bottom).
Source: Authors' elaboration, based on data from Hansaki et al. (2016)

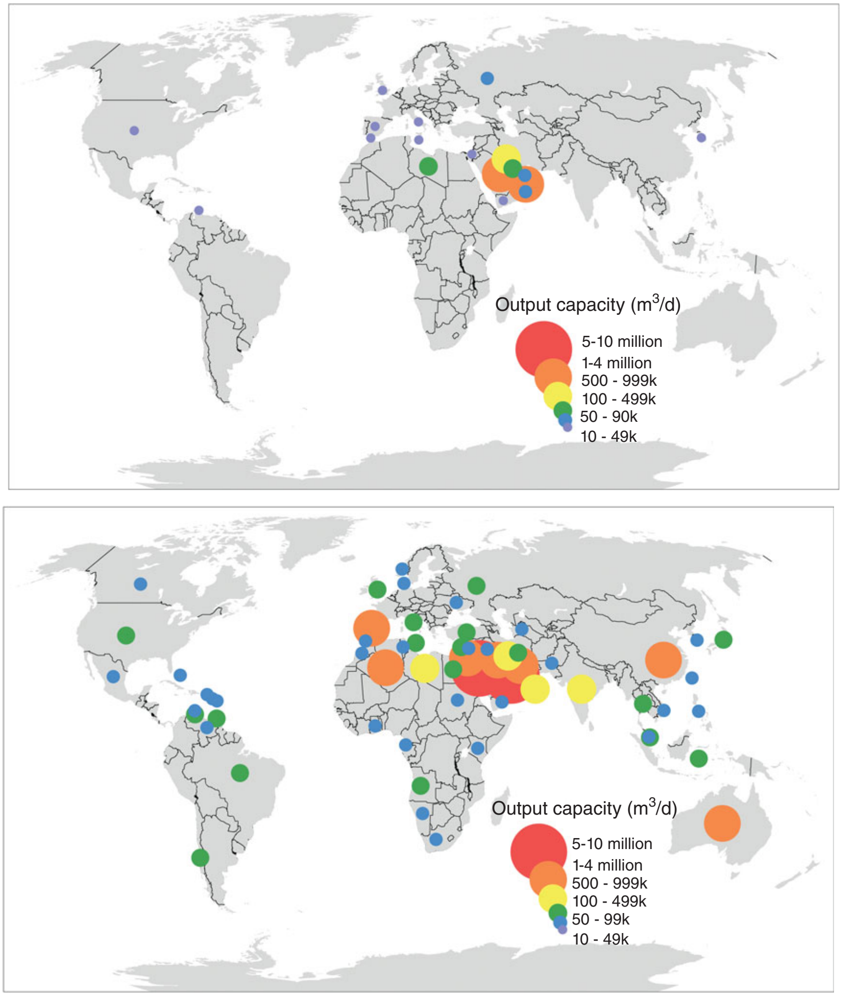

Figure 1.15 Global capacity of desalination plants in 1990 (top) and 2014 (bottom). Source: Authors' elaboration, based on data from Hansaki et al. (2016)

number of medium- and large-scale desalination plants and their capacity by country between 1990 and 2014.

1.8 Demand Management

In Section 1.7, we reviewed several technological means to close the gap between supply and demand. They include storing water during wet years to be used during dry years, treating residential sewage and reusing it in irrigation and for environmental purposes (e.g., river and estuary restoration), and producing drinkable water via desalination of seawater. These measures are often expensive. Demand management means achieving more with a given quantity of water. Examples include providing the incentives to use water saving irrigation technologies, reducing leakage and water loss from conveyance and distribution facilities, more socially desirable allocation of water, and encouraging water conservation. Chapters 3, 4, 5, and 7 focus on aspects of demand management. Here we review the global trends in several of the components of demand management over time.

In the following, we review the time trends in institutions (e.g., water markets), incentives (e.g., water pricing), and regulations (e.g., domestic water laws, standards, restrictions/quotas, and international treaties on shared rivers and aquifers).

1.8.1 Domestic Water Laws

We start with domestic water laws that have been enacted globally (Figure 1.16). Water laws introduce certain regulations in the water sector, which are likely to lead to better management of the resource. We expect that states will turn to legal and institutional reforms when they face a high level of water scarcity and deteriorated quality. Scrutiny of Figure 1.16 suggests that there has been a spike in the number of domestic laws enacted since 1990. This could be the result of either the realization of the scarcity level globally or the increased awareness following the 1992 Rio Declaration.[5] What we do not know is that different types of water laws affect the capacity to deal with water scarcity. This question is an important topic for future research.

1.8.2 International Water Treaties

Many of the river basins are international in nature. There are nearly 260 basins that are shared by 2 or more countries. Such basins often involve conflicts over water ownership and management. Treaties over international water have been signed between riparian states since the mid-1880s (Figure 1.17) in an attempt to address the conflicts over water and the future likelihood that such conflicts would worsen as a result of climate

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[5] Rio Declaration on Environment and Development, The United Nations Conference on Environment and Development, Rio de Janeiro, June 1992.

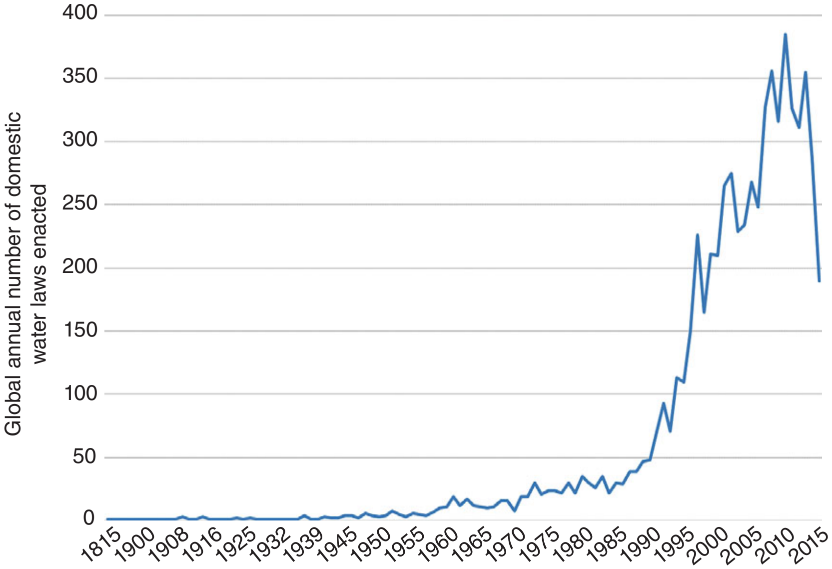

Figure 1.16 Global number of domestic water laws enacted by year, 1815–2015.
Note: The decline in 2015 reflects truncation in documented data that will be filled in future years.
Source: FAOLEX (n.d.)

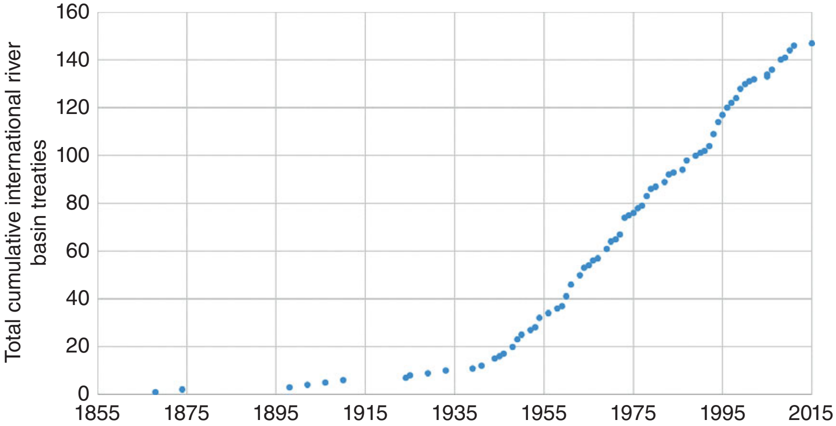

Figure 1.17 Total cumulative number of transboundary river basin water laws and agreements, 1855–2015.
Note: The decline in 2015 reflects truncation in documented data that will be filled in future years.
Source: International Water Law Project (n.d.)

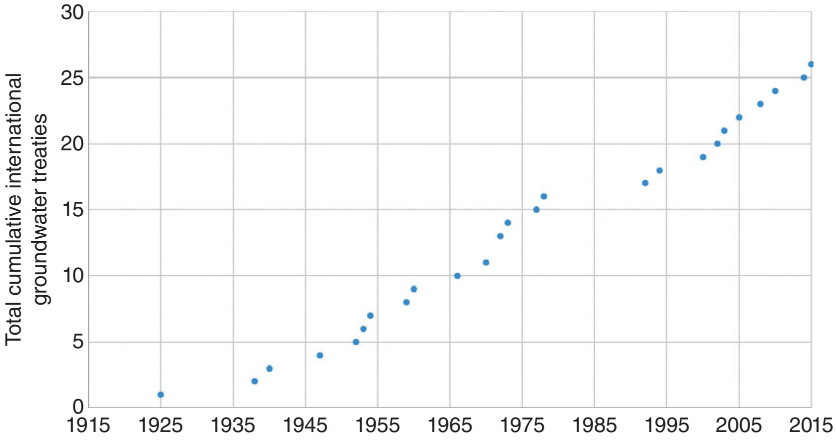

Figure 1.18 Total cumulative number of transboundary groundwater laws and agreements, 1915–2015.
Source: International Water Law Project (n.d.)

change (Dinar and Dinar, 2016). The literature analyzing the performance of international treaties has been expanded over the past two decades, recognizing the importance of these institutions. We dedicate Chapter 9 to addressing the economics of international water. Following a similar motivation, treaties to settle claims over groundwater that are shared by two or more countries have also been attempted, although with less success due to the more complicated nature of groundwater hydrology. Figure 1.18 presents the cumulative number of groundwater treaties signed over the period between 1915 and 2015.

1.8.3 Water Markets

Several additional nonstructural measures that have been implemented globally include water trade and water pricing. Water markets can ease the relative scarcity in a specific region by moving water from a relatively water-abundant region to the water-scarce region or from a relatively low-value use to a relatively high-value use. In order for water markets to perform, property rights for water must be well defined so that individuals know how much water they "own" and can sell in the market.[6]

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[6] This holds in any market transaction, as stressed by the "Coase Theorem," suggesting a simple way to achieve social efficiency (under "certain conditions") in the case of a common pool resource with externality (such as water) that otherwise is hard to regulate. The Theorem states that once property

We start with a recently published dataset on status of water rights allocation in various countries (The Nature Conservancy, 2016). Water rights allocation is a necessary condition for the efficient operation of a water market. As can be seen from Table 1.5, of the nearly 20% of the countries facing water scarcity, there are water rights allocations in only 22 (11%), but evidence of trading exists in only 11 (5.5%).

We selected three countries, Australia, the United States (California), and Chile (Figures 1.19, 1.20, and 1.21), where a water-rights system is in place and there is evidence of water trading over time. Figures 1.19–1.21 demonstrate the extent of water trading in each country/state, subject to the institutional and legal system in place in each, as well as the infrastructure to allow water trade. We do not analyze the differences in performance but rather provide the data. Explaining the differences in market performance is certainly a subject for additional research.

Water rights in Chile are defined in terms of flow (liters per second) in specific stretches of rivers. For example, in 1999/2000 the total value of flow in registered transactions was 160,836.30 liters per second (5,075,495,000 m^3) (Consultorias LIDD, 2013).

Some similarities can be observed across all three markets. First, it is obvious that the period after 2000 is characterized by an increase in the volume traded as well as the number of transactions (in Chile). Second, short-term leases (California) and allocation trade (Australia) are more prevalent than long-term/permanent/entitlement trades. And finally, it is also clear that the market has started to accommodate environment demands only in recent years.

It is difficult to compare the performance of the water markets in Australia, California, and Chile because each country/state has its water-market operation based on different institutional frameworks, water conveyance systems, and rules on how transactions are to be developed and performed. For example, Regnacq et al. (2016) report that trading volumes by the late 2000s were only roughly 3 to 5% of total water use

rights to holders of the resource are identified, quantified, and allocated via any mechanism, and once incentives are provided to allow exchange for payments of units of the resource, social efficiency can be achieved via the market mechanism. The conditions are: (1) it is feasible to assign the property rights (they are identifiable); (2) there are positive net benefits from the reallocation; (3) the transaction cost of coordinating the transfers is low (enforcement and monitoring); (4) no free-rider problem (no one can benefit without paying); and (5) allocation agreements are respected (no cheating).

Table 1.5 *Status of water rights, allocation and trade in water-scarce countries*

Nosignificant water scarcity		Rest of the world	157 (78.5%)
Countries with water scarcity	Water rights, evidence of trading	China	1 (0.5%)
	Water rights, reallocation isallowed, evidence of trading	Western US states, Mexico, Brazil, Peru, Chile, Morocco, Portugal, Yemen, South Africa, Australia	10 (5%)
	Water rights, reallocation is allowed, no evidence of trading	Algeria, Iran, Afghanistan, Zimbabwe	4 (2%)
	Water rights, no evidence of trading	Turkey, Bulgaria, Egypt, Sudan, Ethiopia, Botswana, Argentina,	7 (3.5%)
	No water rights, water allocation is allowed	East Timor, Malaysia, Indonesia, Kirgizstan, Saudi Arabia, Mali	6 (3%)
	No water rights	Italy, Greece, Mauritania, Niger, Libya, Chad, Eritrea, Iraq, Syria, Turkmenistan, Uzbekistan, Tajikistan, Pakistan, Myanmar, Thailand	15 (7.5%)
	Status of water rights, allocation and trade		No. of countries (% of total)

Source: Adapted from The Nature Conservancy, 2016 (fig. 15)

in the urban and agricultural sector in California (Hanak, 2015). And water trading in Australia's Murray–Darling Basin has accounted for one-third or more of total water availability in that basin (AITHER, 2014, 2015; Howitt, 2014). In the case of Chile, in 1999/2000, registered transactions (Figure 1.21) accounted for 14.3% of total available water (nearly 35.43 km^3).

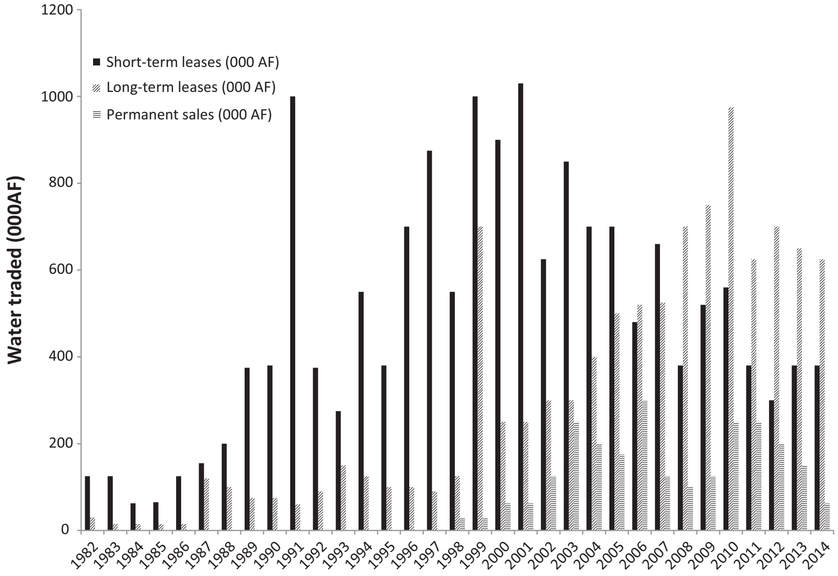

Figure 1.19 Water transfers between water districts in California, 1982–2014.
Note: Volumes include short-term contracts, long-term contracts,
permanent transfers, and water committed but not transferred.
1 Acre-foot = 1,235 cubic meters.
Source: Adapted by authors from Public Policy Institute of California,
www.ppic.org/main/publication_show.asp?i=1177

1.8.4 Water Pricing[7]

Water pricing is considered among the most popular and, at the same time, the most controversial policy intervention used to address water scarcity via demand management. Pricing of water has two key roles, (1) a financial role as a mechanism for recovering the investment and operation and maintenance (O&M) cost of the water system and (2) an economic role, signaling the scarcity value and opportunity cost of water, in order to guide allocation decisions both within and across water subsectors. Under certain conditions, pricing of water could also promote equity objectives. There are big differences among sectors such as irrigation, urban, hydropower, and environment. These differences arise from three causes: (1) The nature of the use of water by the sector; for example,

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[7] See also Chapters 5 and 8.

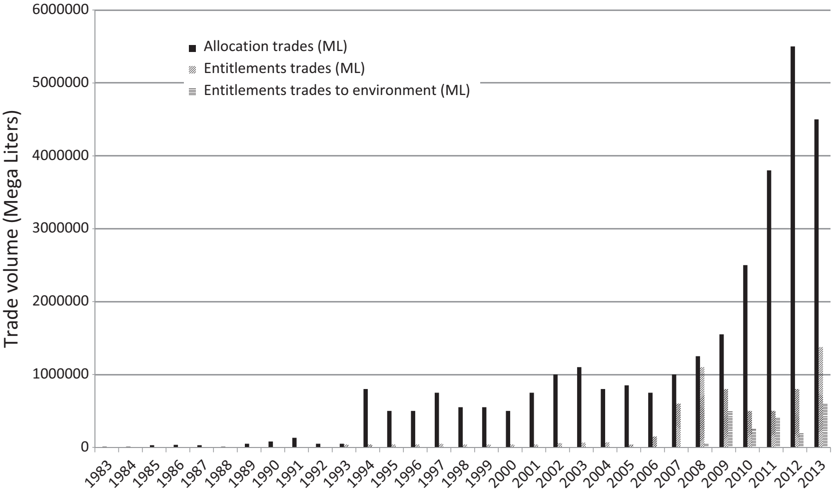

Figure 1.20 Volume of water allocation and entitlement trade in the South Murray–Darling Basin, 1983–2013.

Note: ML=Mega Liter. 1 Mega liter = 1,000 cubic meters. Data for 2012 was not available in the sources used. Water year in Australia starts in July. Therefore, the year marks on the horizontal axis should be read: 1983–1984 for 1983, etc.

South Murray–Darling Basin (SMDB) is presented because the lion share of the transactions in Australia take place in the SMDB. For example, in 2011–2012, 74% of water entitlement trade and 94% of water allocation trade in the Australian water market (1,437,000,000 cubic meters and 429,700,000 cubic meters, respectively) took place in Murray–Darling Basin.

Source: Authors' elaboration based on data in Wheeler et al., 2014 (for 1983–2011) and in Wheeler (2016, personal communication)

irrigation and urban use are consumptive, i.e., they remove the water from the system (rivers, lakes, or aquifers) and often deteriorate its quality by adding pollutants. Water used for hydropower generation is non-consumptive, though it affects water flows and quality. Environmental water use is partly non-consumptive and, in many cases, improves water quality. (2) Ability to identify individual users; for example, while the use by hydropower is transparent, it is hard to identify individual users and monitor their water intake when appropriate infrastructure (e.g., water meters) doesn't exist in irrigation or urban uses. For example, if farmers pump from a shared reservoir, or when households use a central water outlet serving an apartment building, there is no way to assign water use without measuring devices. (3) The unit value of water may differ a lot across sectors, e.g., between urban and irrigation, with urban typically

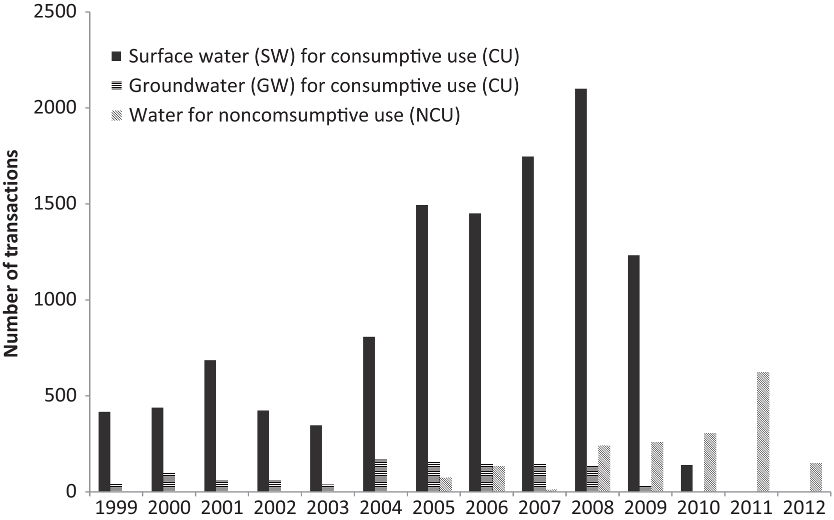

Figure 1.21 Number of registered transactions in water rights in Chile between 1999 and 2012.

Note: Data on non-consumptive trade exists only for 2005–2012.

Source: Elaborated by authors based on data in Consultorias LIDD (2013)

higher than irrigation. Environment and hydropower are typically within this range (Young and Loomis, 2014). In addition to sectoral differences, we must also recognize, especially in the irrigation sector, the impacts that physical locations (e.g., drainage and quality externalities between upstream and downstream users) have on these three aspects.

More in-depth discussion and analysis on water pricing methods can be found in Tsur and Dinar (1997), Dinar and Saleth (2005), and the literature they cite. We will provide in Tables 1.6 and Table 1.7 explanations of water-pricing methods used in the irrigation and residential sectors. More analytical aspects can be found in Chapter 5.

There is scant empirical evidence on the effectiveness of water pricing. In other words, there are very few if any empirical works that compare the impact of the introduction of water pricing or a change in the water pricing method. One such study (Baerenklau et al., 2014) compared the observed reduction in quantities consumed in an urban water district in southern California after a Water Budget Rate Structure replaced a Flat Rate pricing system. They observed a decrease in the total households' water consumption that progressed from 0% in the first year following the reform up to 17% in the third year following the reform. The trend in reduction was

Table 1.6 *Main methods for pricing irrigation water consumption*

Method	Application principles
Volumetric (single rate)	Irrigators pay per volume of water they consume. This method necessitates a water-measuring device. Variation of the volumetric approach include (1) indirect calculation based on measurement of flow time (as from a reservoir) or time of uncertain flow (proportions of a flow of a river) and (2) a charge for a given minimal volume to be paid for even if not consumed.
Volumetric (tiered)	Irrigators pay per volume based on the volume consumed. This method necessitates a water-measuring devise. This is a multi-rate volumetric method, in which water rates vary as the amount of water consumed exceeds certain threshold values. Usually rates are higher for larger volumes. Number of tiers could be greater than two.
Output	Irrigators pay a water fee per each unit of the output they produce. No water-measuring device is needed.
Input	Irrigators pay a water fee per each unit of a certain input used, usually associated with regulation of pollution from use of chemicals. No water-measuring device is needed.
Per unit area	Irrigators are charged per unit of irrigated area, depending on the kind and extent of the crop irrigated, irrigation method, the season of the year, etc. Pumped water is usually charged at a higher rate than gravity water. Farmers are required to pay, in some cases, the per area charges that are also in effect for non-irrigated land.
Two-part tariff	This method involves charging irrigators a constant marginal price per unit of water purchased (volumetric marginal cost pricing) and a fixed annual (or admission) charge for the right to purchase the water. A water-measuring device is needed. The admission charge is the same for all farmers. This pricing method has been advocated, and practiced, where a public utility produces with marginal cost below average cost and must cover total costs (variable and fixed).
Betterment levy	Water fees are charged per unit area, based on the increase in land value accruing from the provision of irrigation water.

Source: Based on Tsur and Dinar (1997) and Dinar and Saleth (2005)

linear. In other studies, Tsur (2015, 2020) uses national-level data from Israel, suggesting that total residential water consumption has decreased by 14% between 2007 and 2011 (from 767.3 to 664.8 million m^3 per year). This decrease is explained by several factors, including a sharp increase in domestic water prices in 2007 to reflect the full cost of water supply (including scarcity cost).

Table 1.7 *Main methods for pricing residential water consumption*

Method	Application principles
Household fixed Fee	A fixed sum is charged to the household periodically (monthly or bi-monthly) no matter how much water the household consumed.
Flat fee (volumetric)	The household is charged a fixed fee per unit of water consumed no matter how much water was consumed.
Inclining block rate (volumetric)	The household is charged, usually, the marginal cost, in blocks, reflecting segments of consumption, with higher ranges of consumption facing higher rates per unit of water consumed. Number of blocks can reach five.
Declining block rate (volumetric)	The household is charged in blocks, reflecting segments of consumption, with higher ranges of consumption facing lower rates per unit of water consumed. The idea behind declining block rate structure is that the utility provides incentives to consumers to consume more water and so to cover better fixed costs.
Water budget rate structure (volumetric)	Similar to Inclining Block Rate except that the first block is flexible and subject to adjustment (volume), based on special circumstances such as family size, livestock on premise, etc. The first block is usually relatively very low in rate per unit of water. Remaining blocks are very high (Dinar and Ash 2015).

Note: In most methods, there are also additional fixed costs such as "connection fees" paid by the household upon establishing the contract with the utility.
Source: Expanded from Dinar and Saleth (2005)

1.9 Role for Economics in Managing Water Resources under Scarcity

This chapter reviewed the interactions between different aspects of social, physical, institutional, technological, and regulatory impacts on water resources use by different sectors globally and in different countries and continents.

Under scarcity of water and other related resources, decisions regarding investments, allocation, use, and sharing the costs and the benefits from investment in water resources and their use become the center of an intersectoral discourse. Economic considerations are relevant for assisting in such decisions.

Economic considerations will be further investigated both theoretically and empirically in the remaining chapters of the book. The various chapters of the book provide the basis for our belief that managing water resources requires a comprehensive approach that, although predominantly economic, relies also on ethical, technical, ecological, sociological, and political considerations.

The various economic tools that we reviewed in this chapter and that will be further developed in the remaining chapters of the book, include pricing of water resources, investment in water infrastructure, regulations of water resources, and the various institutions and management practices that are appropriate to deal with various external shocks, such as climate change, which affect the availability and distribution of water resources.

As such, the remaining chapters address economic principles and methods with a focus on theoretical, empirical, and policy aspects in their application to water management. Therefore, they should be of interest to a wide range of academic readers and, in addition, to water managers and policymakers.

Concepts for Review

- Falkenmark Scarcity Index
- Water stress
- Water scarcity
- Absolute scarcity
- Non-consumptive water use
- Consumptive water use
- Non-structural policy measures
- Structural policy measures
- Domestic water law
- International water treaties
- Water markets
- Water leases
- Water entitlements
- Water pricing (volumetric [single rate], volumetric [tiered], output, input, per unit area, two-part tariff, betterment levy, household fixed fee, flat fee, inclining block rate, declining block rate, water budget rate structure)

Practice Questions

1. Based on the reading in this chapter, suggest and demonstrate three measures of water scarcity. Use the country-level data in the book datasets provided for this chapter to calculate the scarcity indices you suggest for three countries considered to face a priori different levels of scarcity. Do the various indices provide similar ranks of scarcity among the three countries? Why?

2. Economists have suggested water markets as one efficient way to address water scarcity. As we realize from Table 1.5, water markets have not been practiced widely around the world. Using the information provided for Australia, California, and Chile, and exploring more information in the literature cited in this chapter and elsewhere, compare the institutional, physical, and economic conditions in each of these states to discuss performance of the water markets across these three states.
3. One of the pricing methods used in irrigated agriculture is per area (per hectare) charges. Based on the literature cited in this chapter, introduce at least two variations of this pricing method. After explaining the principles for their operations, describe whether or not and to what extent they are able to affect the behavior of irrigators when water scarcity calls for conservation.

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