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Water Shortages

Zhuo Chen
University of Technology Sydney
Graduate School at Shenzhen
Tsinghua University

Huu Hao Ngo
University of Technology Sydney

Wenshan Guo
University of Technology Sydney

Saeid Eslamian
Isfahan University of Technology

PREFACE

Growing environmental problems, including diminishing natural water resources, greater water demand triggered by population growth and urbanization, deteriorated water quality, and highly changing climate, have highlighted the importance of considering the sustainability of water resources and supply systems in both urban and rural areas. Specifically, the world population continues to expand with a growth rate of 1.2% each year, resulting in increased pressure on water quality, safety, and health.

This chapter overviews the current situations in water availability over the world, which is based on information from literature review, recent research studies, and analyses of case studies. It focuses on the issues related to the deficiency of water quantity and deterioration of water quality. With identified problems and challenges, this chapter also discusses some potential responses, opportunities, and solutions to combat water scarcity.

1.1 Introduction

Water is vital to human health and well-being, and to the support of ecosystems, agricultural and industrial development, and the environment. It also has crucial cultural value and social significance [2]. Because of climate change (e.g., flooding, prolonged drought, and severe cold), increasing population, rapid urbanization, and deteriorating water quality, water scarcity is considered one of the most important threats to society and a constraint for sustainable development. Within the next decades, due to continuous economic and population growth, water may become the most strategic resource in many areas of the world, especially the arid and semi-arid regions [28,60]. Based on the International Water Management Institute definition, a very significant portion of the world is projected to suffer from both physical (1000 m^3 per person/annum renewable water supply) and economic water scarcity by 2025.

In Australia, because of water scarcity issues, population losses have been observed in inland rural areas (e.g., north-eastern, south-eastern, and western Australia), which led to a further decline in irrigation services, failure of local businesses, and growing unemployment [34]. In the Middle East, water-related issues have already played an important part in the wide disputes between the regional countries, which could also become the case in Central Asia and parts of Southeast Asia. It is predicted that growing conflicts over access to water may even lead to armed conflicts among nations over control of rivers and aquifers in the future [10,35,51]. Additionally, the United Nations stated that water shortages in terms of reduced water availability, desertification, recurrent flooding, and increased salinity in coastal zones could indirectly lead to internal instability in many areas. Such deterioration may force movement, migration, and/or displacement, triggering social and ethnic tensions in cities and local areas [40]. It is worth noting that the number of "water refugees" around the world has increased from 25 million in 1995 to 50 million in 2010, and the figure will continue to rise steeply over the next decades [30,35]. In addition, an Australian report pointed out that drought is also a significant cause of suicide and mental illness for Australian farmers and rural communities [34].

In light of potential water shortages, some cities have increasingly recognized the significance of considerable water conservation and water demand management as a long-term water supply strategy. However, as water conservation is inadequate to close the water supply–demand gap in some cases, sustainable management solutions and technological options in driving green growth for augmenting existing water supplies should be considered, including the exploitation of alternative water resources such as desalinated and recycled water, and the development of aquifer storage and treatment of unusable water [53]. Moreover, other innovations should also be taken into account, which can promote the water market toward increased efficiency, productivity, and enhanced environmental outcomes to balance the environmental, economic, and social issues [2].

1.2 Current Situations in Water Availability

The availability of water in sufficient quantity and adequate quality is indispensable for human beings and the functioning of the biosphere [37].

1.2.1 Deficiency of Water Quantity

The surface water and groundwater constitute the major constant water resources for water supply in both urban and rural areas. As shown in Figure 1.1, in a natural water cycle, rainfall normally enters the surface water system via precipitation, namely rainwater, or from the upper catchment or rivers, namely stormwater, and then leaves the system through evaporation, transpiration, downstream outflow, or surface runoff. At the same time, surface water can contribute to groundwater replenishment through seepage and infiltration [56]. Although the hydrological cycle links all waters, surface water and groundwater are usually studied separately and represent different development opportunities.

As can be seen from Figure 1.2, the total water resources in the globe are estimated to be 43,000 cubic kilometers per year (km^3/year), which are distributed throughout the world unevenly on the basis of climate and physiographic structures [23].

When it comes to the continental level, America (including North America, Central America and the Caribbean, and Southern America) has the world's most abundant freshwater resources (45%), followed by Asia (28%), Europe (15.5%), and Africa (9%). It is widely accepted that the per capita water resource can be used as a parameter for a reasonable evaluation of water supply conditions. Thus, from the perspective of per capita resources in each continent, the Thelon River basin in Canada's Northwest Territories has the highest per capita water resource at around 15,000,000 m^3/person/year, while the Yaqui River in Sonora, Mexico has the lowest per capita water resource at only 173 m^3/person/year. The Yellow River basin in China is also among the watersheds with very low per capita water resource at 361 m^3/person/year [65,66]. Africa and Asia only occupy 5000 and 3400 cubic meters per year (m^3/year) of water resources per inhabitant, respectively, compared with 24,000 m^3/year of that in America (including North America, Central America and the Caribbean, and Southern America) [23]. In highly populated countries such as China and India, the per capita water availability is as low as 1700–2000 m^3/year [27].

Once a country's available water resources drop below 1700 m^3 per person per year, the country can be expected to experience regular water stress, a situation in which disruptive water shortages can frequently occur. When the available water resource drops below 1000 m^3/person/year, the situations can be more severe and lead to problems with food production and economic development. Moreover, if the amount of water available per capita drops below 500 m^3/person/year, countries face conditions of absolute water scarcity. By 2025, it is projected that, assuming current consumption patterns continue, at least 3.5 billion people, or 48% of the world's population, will live in water-stressed river basins. Of these, 2.4 billion will live under high water stress conditions [65,66].

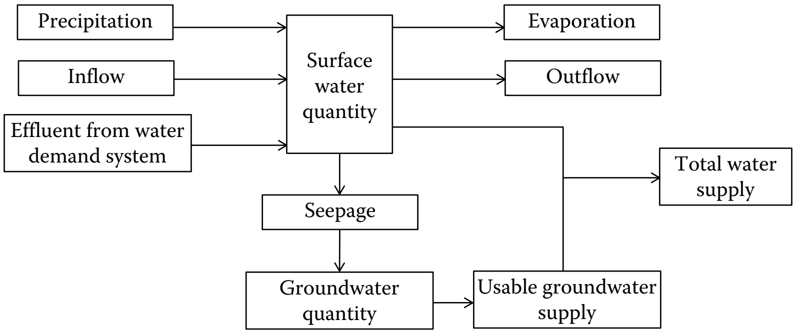

FIGURE 1.1 Schematic diagram of a generic water supply system. (Reprinted from Tan, Y.Y. and Wang, X., An early warning system of water shortage in basins based on SD model, *Procedia Environmental Sciences*, 2, 399–406. Copyright 2010, with permission from Elsevier.)

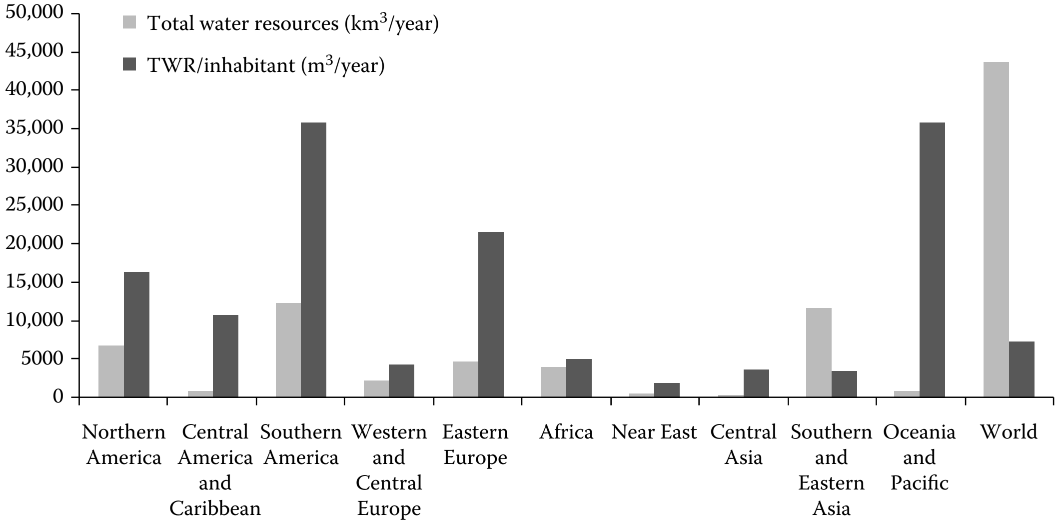

FIGURE 1.2 World water resources by region. (Data adapted from Food and Agricultural Organization. 2003. *Review of World Water Resources by Country*. Food and Agricultural Organization of the United Nations, Rome, Italy.)

It is recognized that water stress and sustainability are a direct function of the water resources available and of water withdrawal and consumption [24]. The increasing water needs/demands because of population growth, rapid economic development with land overuse, and climate change are the major drivers of increasing global water stress [24]. The world population is predicted to grow from 6.9 billion in 2010 to 8.3 billion in 2030 and 9.1 billion in 2050. By 2030, food demand is predicted to increase by 50% while energy demand from hydropower and other renewable energy resources will rise by 60%. These issues are interconnected and likely to lead to increased competition for water between the different water-using sectors. Currently, agricultural irrigation continues to play an important role in food production, which accounts for 70% of all water withdrawn by the agricultural, municipal, and industrial sectors. To meet the future water and food demand in this sector, innovative technologies will be needed to improve crop yields and drought tolerance, produce smarter ways of using fertilizer and water, new pesticides and nonchemical approaches to crop protection, reduce postharvest losses, and ensure more sustainable livestock and marine production [61].

Furthermore, the rapid global urbanization has led to increasing growth of urban water use, especially domestic water consumption, giving rise to tension in urban water supply and demand (Figure 1.3). The world's cities are growing at an exceptional rate and urbanization is a continuum. Ninety-three percent of urbanization occurs in poor or developing countries [14]. The accelerating process of urbanization also translates

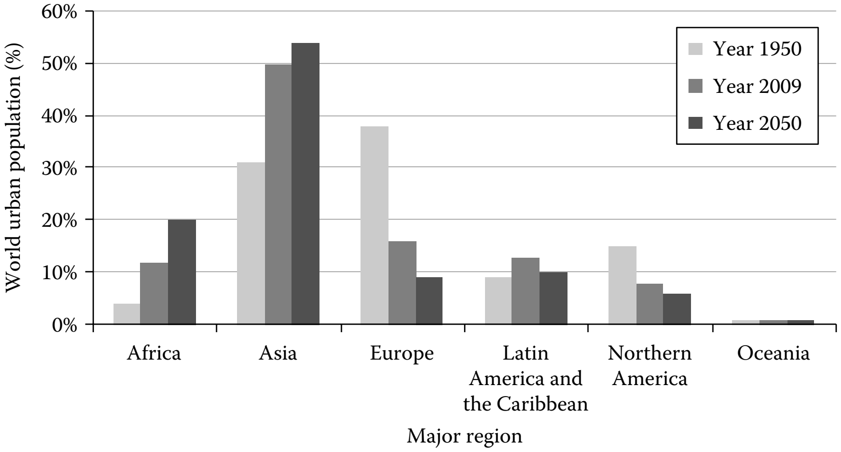

FIGURE 1.3 Distribution of the world urban population by major regions. (Data adapted from Department of Economic and Social Affairs. 2010. *World Urbanization Prospects the 2009 Revision*. United Nations, New York.)

into increased exposure to poorly designed or managed water systems and poor access to hygiene and sanitation facilities in public settings. For instance, in China, rapid urbanization is the dominant social and economic phenomena since the late 1970s. The urban population in China increased from 172.45 million in 1978 to 665.58 million in 2010, and its proportion in total population increased from 17.92% to 49.68%. Because of the growing urban population and industries, about two-thirds of China's 661 cities are short of water, of which more than 110 are suffering from severe water shortage. Hence, it is necessary to study the interaction of urbanization and water utilization so that those areas with water problems could achieve a sustainable urbanization [71].

Climate change is posing an additional challenge to urban water supplies. It may lead to increases in temperature, higher evaporation rates, and lower rainfall, exacerbating water-related disasters. For instance, this is likely to result in increased rainfall variability, increased risk of drought, and reduced availability of water for inland regions [29]. Consequently, surface water and groundwater resources are likely to be affected by these changes. Ceres [9] listed the observed changes in North American water resources during the past century. These include (i) 1–4 week earlier peak streamflow due to earlier warming-driven snowmelt; (ii) decreased proportion of precipitation falling as snow; (iii) reduced duration and extent of snow cover and ice cover; (iv) increased annual precipitation in most of North America but decreased annual precipitation in places like the Central Rockies and southwestern United States; (v) declined mountain snow water equivalent; (vi) increased frequency of heavy precipitation events; (vii) reduced runoff and streamflow; (viii) increased temperature of lakes; (ix) salinization of coastal surface waters; and (x) increased periods of drought. As can be seen, the climate change contributed to increases in intensity, duration, and spatial extent of droughts associated with higher temperatures, warmer sea surface temperatures, changes in precipitation patterns, and diminishing glaciers and snow pack [9].

Similarly, in Australia, climate change is likely to increase the difficulties that the country faces to secure adequate water supplies for cities and irrigation. Specifically, climate change projections showed increased potential evaporation, a tendency for decreases in winter–spring rainfall over the southern half of the continent, and a tendency for increased summer/autumn rainfall in northern Australia. In southern Australia, where winter and spring rainfalls are more important and competition for water between natural and human uses is already high, reductions in water supply appear to be much more severe [10].

With respect to surface water, water may be abstracted from artificial reservoirs, dams, rivers, lakes, and household water tanks. Notably, the rivers and surrounding watersheds are the major sources of water for agricultural irrigation, industrial and residential purposes, ecological/environmental flows, drinking, and other uses. Table 1.1 lists the major rivers in the world together with their drainage area and average annual runoff. Nevertheless, major river levels have dropped significantly at present and the existing water supply is often insufficient to meet the increasing water demands particularly in times of low rainfall, in both rural and urban areas. For instance, in Australia, the recent drought conditions across much of southeastern Australia during 2008–2009 have directly led to a 30% reduction in fresh water supply volumes compared to 2006–2007. It is estimated that the rivers and streams in the Murray-Darling Basin may have flows reduced by up to 30% by 2050, and 45% by 2070, which will further increase competition for already scarce water resources [29].

TABLE 1.1 Major Rivers in the Globe with Their Average Annual Runoff

River	Length (km)	Drainage Area (km^2)	Average Annual Runoff (km^3)	References
Murray-Darling, Australia	3780	1,056,000	530.0	[42]
Yangtze, China	6300	1,808,500	951.3	[44]
Yellow, China	5464	752,433	66.1	[44]
Mekong, China	4350	810,000	505.0	[67]
Volga, Russia	3692	1,380,000	254.4	[67]
Yenisei, Russia	5539	2,580,000	618.1	[67]
Ob-Irtysh, Russia	5410	2,990,000	403.7	[67]
Lena, Russia	4400	2,490,000	539.2	[67]
Nile, Africa	6650	3,254,555	161.0	[67]
Congo-Chambeshi, Africa	4700	3,680,000	1318.0	[67]
Niger, Africa	4200	2,090,000	301.8	[67]
Mississippi, North America	6270	2,980,000	530.0	[67]
Mackenzie, North America	4241	1,790,000	324.8	[67]
Amazon, South America	6400	7,050,000	6911.6	[67]
Paraná, South America	4880	2,582,672	567.6	[67]

As a result, water restrictions across Australia have been invoked more often and at deeper levels, affecting many irrigation supply services. More seriously, the possibility of acute supply failure has become increasingly apparent and some smaller towns have actually run out of water [68]. Likewise, Northern China's largest natural freshwater lake, Lake Baiyangdian, is both disappearing and grossly contaminated [27], and water crises have occurred in more than 400 Chinese cities at the beginning of 2000 [74].

Moreover, groundwater is a precious and indispensable water resource that has become the principal resource in many cities around the world. Due to advances in technology that decline extraction costs and offer more reliable water delivery, as well as subsidies from the government and local authorities for power and pump installation, the privately owned and managed tube wells are also widely distributed. In Asia, more than 1 billion people rely on groundwater for drinking. Besides, in India and China, which account for 40% of the world's irrigation, the area irrigated by groundwater rose from about 25% in the 1960s to over 50% in the 1990s. This has led to the overexploitation of groundwater resources in the semi-arid regions where water tables have been falling at an alarming rate, often 1–3 m per year [6]. Particularly, in northern part of China, over-pumping and contamination of groundwater has forced cities and businesses to dig as deep as 120–200 m to find clean adequate supplies, compared with only 20–30 m deep a decade ago. Apart from additional costs caused by digging and maintenance, groundwater funnels have been reported and a remarkable one in the northern area of China, with an area of 50,000 km^2, is considered to be the largest in the world [27,74].

In Europe, groundwater takes up approximately 65% of total water supply. Particularly, in Berlin, Germany, approximately 70% of the water for domestic and industrial uses comes from groundwater. In the Middle East and Africa, many countries such as Saudi Arabia, United Arab Emirates, Libya, and Oman also depend heavily on groundwater [36,49]. Nonetheless, overextraction has triggered groundwater depletion and related environmental problems. It was estimated that in some regions of the Mediterranean, 58% of coastal aquifers suffer from saline ingress so that agricultural industries were severely affected [18]. For instance, the Disi Aquifer between Jordan and Saudi Arabia is being developed by Jordan, with plans to extract unsustainable amounts of a nonrecharging water resource. The aquifer is likely to be depleted within 50 years [50]. Furthermore, ground subsidence has been observed in some big cities such as Shanghai and Mexico City, which can be a huge threat to construction and buildings [6,13].

To optimize the surface water and groundwater management and match the water resources with the water demands over the short and long term, the linkages between precipitation, surface water runoff, aquifer recharge, and pumping and the correlations between urban water demand, population variation, and climate change should be established [73].

1.2.2 Deterioration of Water Quality

Water quality is inextricably linked with water quantity as both are key determinants of supply. Poor water quality can impact water quantity in a number of ways. For example, polluted water that cannot be used for drinking, bathing, industry, or agriculture may largely reduce the amount of water available for use in a given area. When the water is heavily polluted, some additional costs are required to treat and purify the water for meeting the quality standard of discharge and reuse [61].

It is significant that water quality deterioration has been observed in rural and urban areas throughout Africa, Asia, and Latin America [58]. The degradation of water resources can have a far-reaching effect on environmental quality, human health, and even on global warming [48]. The deteriorating quality of water resources is an immediate result of wastewater discharge from cities and industry. Half of the world's rivers and lakes are polluted due to a lack of proper sanitation. For instance, industrial wastewater discharge can be chronic or accidental. Some chemicals that are used for health care such as endocrine disrupting compounds and pharmaceutical active compounds are increasingly discharged to municipal sewage. These substances are synthetic and have received much concern due to their uncertainty, toxicity, and persistence. They are difficult to trap using conventional treatment methods. Thus, the potential risks are sometimes underestimated [19,41,62].

For surface water such as rivers and lakes, overuse can lead to increased concentration of harmful substances present in the water due to pollution or mineral leaching [61]. For instance, India's diversion of water from the Ganges River over the past 30 years has reduced the water available to its other neighbor, Bangladesh, resulting in increased salinity, a decline in river fish, droughts, declining sedimentary deposits, decreased agricultural productivity, and loss of land to the sea [50]. Additionally, water resources have also been contaminated by pollution from agriculture. A major cause could be the indiscriminate use of chemical fertilizers. Particularly, some inorganic chemical pollutants (e.g., sodium, potassium, calcium, chloride, bromide, and trace heavy metals) are of high concern, as highly saline irrigation water can severely degrade the soil and the accumulation of heavy metals in soil can pose threats to the food chain [13,48]. The unsustainable irrigation activities might also result in groundwater contamination and environmental degradation. Moreover, owing to inappropriate management, water quality deterioration has also been detected in a wide variety of water supply types including piped supplies, boreholes, hand-dug wells, and even traditional water collection sources such as plastic and metal buckets [58].

Besides, water quality can be affected by excessive groundwater pumping through increased concentrations of naturally occurring compounds that become dangerously high as the amount of water dwindles. On the other hand, water quality can be affected by increasing salinity levels as a result of saltwater intrusion into coastal aquifers. Saltwater intrusion will not only reduce the amount of water available for human consumption, but also impact the other uses including agricultural and industrial purposes [61].

It is worth noting that in developing countries, unclean water causes severe health threats to millions of people, particularly causing challenges for children. More than 2.6 billion people (42% of the total population) lack access to basic sanitation facilities at present and are exposed to contaminated water sources, which contain excessive chemical compounds and high concentrations of pathogens (e.g., parasites, bacteria, and viruses). These water-borne substances can lead to a wide variety of diseases (e.g., diarrhea, typhus, guinea worm, malaria, and others). It is reported that 2.2 million deaths per year, 1.46 million of which are children, are caused by sanitation-related diseases, poor hygiene conditions, and unclean water [57,72].

Therefore, it is essential to plan coping strategies effectively together with interventions within minimized investments, especially for rural and regional areas [55]. Baguma et al. [5] conducted a social survey study in Uganda, Africa to examine the efficient water management in developing countries and found that the level of per capita income and involvement of women in water-related operation and maintenance partly influenced the safe water supply in households. They also indicated that the large size of a family could play an important role in the provision of safe water as a large number of active laborers in a family can help to remove unhygienic items from water storage systems or assist in removing waste that could facilitate the growth of pathogens. In addition, Ujang and Henze [59] addressed the use of practical measures for preservation of public health associated with water supply, sewage, solid waste management, and other public health services. By June 2010, there were 1519 centralized municipal wastewater treatment plants (WWTPs) in China and 18 plants were added each week.

Nevertheless, other researchers claim that the conventional management approaches using extensive sewer networks and big sewage treatment plants (STPs) require a high degree of legal enforcement, high capital, operating, maintenance cost, and in-house water and sewer connections and will not be sustainable in nature. There is a need for sustainable sanitation, which is technically manageable, sociopolitically appropriate, systematically reliable, and economically affordable which utilizes minimal amounts of energy and resources with the least negative impact and recovery of useable matters. The concepts of sustainable sanitation emphasize three major components: separation of pollutants at the source, decentralization of facilities, and reuse of by-products, especially treated wastewater and sludge. Since in many rural regions of China, no public wastewater treatment facilities are available and water supply and sanitation infrastructures are still in development stages, it is an ideal situation to start a new infrastructure with a new framework [59]. The components of sustainability in water supply and sanitation include policy and institutional, economic, environmental, technical, and sociopolitical aspects.

1.3 Responses and Opportunities Related to Water Shortage

To combat the water scarcity issues over the world, some incentives that improve water use efficiency and productivity such as technical innovations in developing alternative water resources should be considered. Additionally, the sustainable water management approaches have also been increasingly applied to explore and analyze existing and future water-related issues, as well as to support water managers and decision-makers to put forward solutions for potential situations [16]. The sustainable management generally incorporates the environmental, economic, social, and energy and resource sustainability [15]. To particularly address water shortage problems, some management strategies on demand–supply estimation, integrated water resources management and pricing, and policy and investment decisions should be increasingly discussed and established.

1.3.1 Identification and Evaluation of Possible Water Resources

Previously, the traditional solutions of increasing water supply and providing water security mainly focused on the importation of distant water resources or building additional water dams. For instance, in Asia, Singapore has been importing water from Malaysia under bilateral agreements since 1927. The imported water makes up around 30% of Singapore's total supply [17]. However, increasing supply from traditional sources can be very costly and tedious due to regulations, negotiations, competing users, and high marginal costs of extraction and pumping. Moreover, high infrastructure and energy costs can also increase the difficulty of importing water from distant sources [53,73].

In addition, building large dams for adding additional water supply has been considered unsustainable, which has not only presented numerous issues to the environment such as flooding, deforestation, and reduced pastureland, but also exerted negative impact on the livelihoods of local populations. It is estimated that 40–80 million people have been displaced by the construction of large dams worldwide [21]. Currently, owing to the technical possibility and economic affordability of previously prohibitively expensive technological alternatives, many countries, regions, and cities have increasingly recognized the significance of water conservation, water recycling and reuse, and desalination of brackish or ocean water as long-term water supply strategies [53].

1.3.1.1 Water Conservation

Water conservation is regarded as an environmentally friendly solution. The major advantages of local potable water use reduction, minimized cost of water supply network expansion, and cross-connection as well as leakage checking and repair have been widely acknowledged [47]. Municipalities should routinely promote actions to lower domestic water consumption and cities should require water-saving fixtures in all newly constructed homes, offices, and public buildings and should offer incentives to those who retrofit with these technologies [3].

In industrial sectors, there is a significant variation in the per-production-unit water consumption by different enterprises. The improvement of productivity and efficiency under water scarcity situations requires an acceleration of effort to reduce demand, including water withdrawals by industry and energy producers [3]. With respect to public sports and recreational facilities such as swimming pools, the implementation of water saving strategies such as dual flush toilet systems, water saving and flow regulation devices in shower heads, and filtration systems and pool covers to reduce evaporation are likely to minimize water consumption and the environmental footprint. These actions are being successfully implemented in many newly constructed aquatic centers [33].

Notably, as residential areas are also the main users of urban water, the development of effective strategies and policies to obtain detailed knowledge of water consumption regarding how and where residential water is consumed can provide a greater understanding of the key determinants of each and every water end use and, in return, will allow for the development of improved long-term forecasting models [38]. By implementing water use restrictions as well as regulations and reducing losses due to leaks at the household level, water consumption has been successfully reduced by approximately 22%–40% in many countries such as Australia, France, Canada, and Jordan [39].

Generally, showering is reported as the highest indoor consumption category, being 33% or almost 50 (L/p/d) Litres of water per person per day [39,69]. This water end use category has the potential to be substantially reduced in drought periods. Specifically, the replacement of low efficiency showerheads with higher ones will result in a considerable reduction in average daily shower consumption in the household. From an economic perspective, showerhead retrofit programs and conservation awareness campaigns are considered as least cost potable water saving measures that can be easily implemented by the water business or authority. In addition, laundry is regarded as the second largest indoor user of water [4]. The choice of washing machine type is the main factor affecting the annual water consumption in laundry, and front loaders typically consume less than half as much water per wash as top loaders. The higher occupancy (large families) can lead to lower total per capita water use compared with single person households [12,25,70,69].

1.3.1.2 Water Recycling and Reuse

With the rapid development of advanced wastewater treatment technologies such as membrane filtration in the last 10–15 years, many cities and regions of developed countries including North America, Australia, the Middle East, the Mediterranean, Asia, and Africa have considered water recycling and reuse as an alternative water resource to combat water scarcity issues. Some planned recycled water schemes have also been observed in many developing countries, especially in intensive agricultural areas [11,22]. These are due to the increased knowledge and understanding on the merits of recycled water (e.g., alleviation of the pressure on existing water supplies, reduction of effluent disposal to surface and coastal waters, and provision of more constant volume of water than rainfall-dependent sources). As more and more countries begin to notice the prospect of the fit-for-purpose recycled water reuses, the global water reuse capacity is projected to rise from 33.7 (GL/d) Giga Litres per day in 2010 to 54.5 GL/d in 2015 [44].

However, the real applications of recycled water vary in different countries which depend heavily on available treatment levels, current water supply status, environmental conditions, and public perceptions. Notably, agricultural irrigation currently represents the largest use of recycled water throughout the world. With respect to reuse categories, approximately 91% of the water was used for irrigating crops and pastures (e.g., cotton and vegetable growing, grain farming, fruit and tree nut growing), while 9% was used for other agricultural purposes such as stock drinking water and dairy and piggery cleaning [46].

Moreover, landscape irrigation is the second largest user of recycled water in the world currently, although the particular water demand for different countries and regions varies greatly by geographical location, season, plants, and soil properties. The specific applications include golf course uses, public parks, schools and playgrounds, and residential area landscape uses. Apart from irrigation purposes, recycled water has also been successfully applied to industrial sectors in Japan, the United States, Canada, and Germany since the Second World War for more than 70 years. Recently, industrial use is the third biggest contributor to recycled water consumption. The major categories associated with substantial water consumption include cooling water, boiler feed water, and industrial process water [11]. Furthermore, other applications on environmental flow regulations and residential purposes (e.g., fire protection, toilet flushing, car washing, and clothes washing) are being widely practiced. Residential applications are observed mostly in well-developed countries and regions, especially in highly urbanized areas where dual pipe systems have been established [1].

Notably, some sustainable management or control approaches can be carried out in existing or future recycling schemes to reduce water consumption and overall environmental footprint further. In addition to wastewater reuse, capturing and storing rainwater and stormwater can also reduce the demand on freshwater significantly. For instance, it is suggested to construct micro-dams along major waterways to store floodwater during winter seasons to reuse it again in the summer farming seasons as complementary irrigation water. This action will benefit the farmers and raise the national food sufficiency [31]. However, the rainfall-dependent water resources are highly variable and subject to climate conditions.

1.3.1.3 Desalination

The desalination of saline water has been increasingly recognized as one of the new water resource alternatives to provide freshwater for many communities and industrial sectors in a number of countries around the world. In desalination technologies, saline water is separated into two parts using different forms of energy. The potable water with a low concentration of dissolved salts is produced in one part. In the other part, the brine concentrate is collected, which has a much higher concentration of dissolved salts than the original feed water [7,52]. Remarkably, the desalination market is growing very rapidly with a growth rate of 55% per year. In some arid, semi-arid, and remote regions, desalination has now been able to successfully compete with conventional water resources and water transfers for potable water supply. The large centralized or dual purpose desalination plants are shown to be more economical and suitable for large density population areas [52,26].

Regarding the treatment approaches, the majority of water desalination processes can be divided into two types: phase change thermal processes and membrane processes, both encompassing a number of different processes. All are operated by either conventional or renewable energy sources to produce fresh water [52]. On the other hand, thermal desalination that is based on the principles of evaporation and condensation accounts for about 30%–50% of the entire desalination market [26,20].

TABLE 1.2 Market Historical and Forecast of Desalination Systems

Project Type	2006–2010 (billion USD)	2011–2015 (billion USD)
Seawater reverse osmosis (RO)	9.92	15.48
Seawater multieffect distillation (MED)	3.03	4.04
Seawater multistage flash distillation (MSF)	8.39	7.07
Small thermal	2.06	2.33
Brackish RO	1.43	2.18
Ultrapure RO	0.21	0.30
Total (billion USD)	25.04	31.40

Source: Reprinted from Ghaffour, N., Missimer, T.M., and Amy, G.L., *Desalination*, 309, 197–207, 2013. Copyright 2013, with permission from Elsevier.

In the near future, desalination has great development potential on a global scale. This is attributed to the fact that desalinated water is a new water source that has an essentially unlimited capacity. Table 1.2 shows the overall desalination historical development and market potential in the following years. As can be seen, about 50% of the investments are for reverse osmosis (RO) projects because of the lower capital and water costs and smaller footprint sizes [8]. Thermal processes will also continue to be utilized, especially where energy is available at low cost, and multiple-effect distillation (MED) is likely to replace multi-stage flash desalination (MSF) in future projects [26]. However, desalination processes normally consume a large amount of energy [20]. As many areas often experience a shortage of fossil fuels and inadequate and unreliable electricity supply, the integration of renewable energy resources such as geothermal, solar, or wind energies in desalination and water purification is becoming more viable and promising. Besides, the development of new low cost technologies such as adsorption desalination, improvements in membrane design, and system integration and utilization of low grade waste energy will likely decrease the desalinated brackish water cost. The cost reduction as well as minimization in energy consumption will further benefit the smooth expansion of the desalination market.

1.3.2 Water Demand and Supply Analysis

To calculate the water resources amounts and utilization needs, a series of analyses including the water consumption balance analysis, available water resources analysis, supply–demand water resources balance analysis, and over water resources security analysis can be performed. Based on Reference 56, the total water demand in a socioeconomic system can be generally figured out by the following equation:

$$D = D_I + D_A + D_D + D_E - WC - RW - DE \tag{1.1}$$

where D_I is the monthly total industrial water demand, D_A is the monthly total agricultural water demand, D_D is the monthly total domestic water demand, D_E is the monthly minimum ecological flow, WC is the total water savings from conservation strategies, WR is the total recycled water, and DE is the total desalinated water. Accordingly, the early warning level for water shortage can be classified according to the supply–demand ratio (R_{sd}) as follows:

$$R_{\text{sd}} = TS/D \tag{1.2}$$

where R_{sd} is the supply–demand ratio, TS is the monthly total water supply, D is the total water demand and $R_{\text{sd}} \geq 1$ indicates the safety level [56].

Moreover, sensitivity analyses using extreme hypothetical socioeconomic and water management scenarios (e.g., population control, economic recession, industrial watershed, no surface water withdrawal, and no groundwater withdrawal) can provide insights to identify key drivers and effective strategies [28].

1.3.3 Integrated Water Resources Management

There is growing evidence that water scarcity issues can be created or intensified by unsustainable decisions to meet increasing water demands. Thus, the integrated water resources management (IWRM) has become an important framework in sustainable development and management of water resources. It involves the consideration of various possible water sources to satisfy the demands of different users, environment protection, and land and urban planning. This allows the capture of added aesthetic, ecological, economic, energy production and conservation, recreational, social, and other benefits in ways that have never been realized before [54]. The key principles in IWRM include

- Freshwater is a finite and vulnerable resource, essential to sustain life, development, and the environment.
- Water development and management should be based on a participatory approach involving users, planners, and policy makers at all levels.
- Women play a central part in the provision, management, and safeguarding of water.
- Water has an economic value in all its competing uses and should be recognized as an economic good.
- The important components in IWRM include economic efficiency, equity, and environmental sustainability [32].

Presently, based on the IWRM concept, some models have been developed such as the dynamic models, linear programming, simulation-based models, multilevel optimization techniques, and nonlinear programming. Particularly, the system dynamics models can facilitate understanding of the interactions among diverse and interconnected subsystems that drive dynamic behaviors. With identified problematic trends and their root drivers, these models are shown to be beneficial in water resources planning and management [28]. Besides, Wang and Huang [63,64] have utilized stochastic fuzzy programming approaches for water resources allocation problems. The developed methodology was applied to case studies and a set of solutions under different feasibility degrees was estimated based on economic efficiency, degree of satisfaction, and risk of constraint violation. Likewise, Pingale et al. [45] have applied the integrated urban water management model considering climate change (IUWMCC) for the optimum allocation of water from various water supply sources to satisfy the water requirements of different users along with considering various system and geometric constraints. Consequently, the application of IWRM concepts and subsequent models would be useful for decision makers or local authorities in optimum planning and utilization of water resources.

1.3.4 Water Pricing, Policy, and Investment

Water pricing reforms and incentives need to be performed to encourage economic efficiency in service delivery, investment, and water use. This involves regulations to ensure that

- Pricing sends a signal for efficient water use and investment.
- Prices are high enough to recover costs of operating and renewing water infrastructure and to ensure that autonomous water businesses are financially viable and able to invest.
- There are strong incentives and disciplines to ensure that costs are not excessively high [43].

At present, less than full cost recovery is the common feature of water utilities servicing residential areas. Many local utilities are not coupling the costs of supplying water to price increases but charging prices significantly lower than those in major urban areas. For long-term sustainable management, they should reduce nonrevenue water, improve water services by establishing autonomous and accountable providers, and increase price signals by improving metering and collection of service charges [3]. The movement to full cost recovery will allow many water businesses to fund major new investments from their customers substantially more than they would have otherwise been. Furthermore, wherever feasible, for IWRM, tariffs should be differentiated to reflect key cost drivers in meeting environmental objectives. Well-designed tariff structures with effective information, education, and communication programs can reduce water demand substantially. In addition, ensuring that pricing of access to water, wastewater, and desalination infrastructure by third parties is efficient will be important in promoting innovation in IWRM [13,43]. Without sufficient incentives and pricing reforms, water utilities, even the larger ones, will become unsustainable and water quality and security will suffer as a result. At the same time, government and local authorities should also invest in inclusive public awareness programs to highlight water issues [3].

1.4 Summary and Conclusions

The need for water continues to become more acute with the changing requirements of an expanding world population. To combat water scarcity issues, sustainable water management has received great attention in recent years. This requires water-related decision making to be performed on a holistic view of the problems due to the multitude of complex, interlinked, socioeconomic, and biophysical subsystems within watershed systems. In addition to rational planning and management of existing water supplies from traditional water resources, the significance and feasibility of potential alternative water resources and long-term water supply strategies should also be highlighted. The solutions may include water conservation, water recycling and reuse, and desalination. However, the smooth establishment and implementation of a sustainable water management framework, principles, and approaches are still challenging, especially in less developed areas. Consequently, before the implementation processes, additional assessment and reforms on water demand–supply analysis, integrated water resources management, and water pricing and corresponding governmental policies are highly recommended.

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