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Global Water Scarcity and the Need for "New Water"

1.1 Introduction

The title of this book includes the word *desalination*. Dictionary.com (2012) defines desalination as "the process of removing salt, esp from seawater so that it can be used for drinking or irrigation." Thus, desalination is a process that produces potable water. The reader should keep in mind, and this will be discussed later in the book, that there are other processes available for producing potable water, many of which are *currently* uneconomical. For this reason, the book primarily deals with desalination. The general topic of potable water is also considered and is addressed in several of the paragraphs to follow.

The world's total water is enormous compared with the presently conceivable needs of man, yet there is a growing water problem. Of the 1.39 billion km^3 (332 million mi^3) of water in the Earth's crust 99% is salty and useful neither for irrigation by present techniques nor for the majority of man's other needs.

Rain provides many times the world's annual water needs, but fresh water supplies vary widely over the Earth and from time to time in a given region. This accounts for the "water problem" that exists as the Earth's population continues to grow. In the United States, the actual "consumptive use" is approximately 12%–18% of the potential supply. Water prices are low, and on a statistical basis there should be no water shortages for many years. These average figures are of little comfort to the people of arid regions, however, and the United States, though relatively well supplied with water, is now beginning to turn to sources other than rainfall and runoff to meet growing water demands. The Southwest has too little water to support rapid population expansion. California has embarked on multi-billion dollar projects to bring water nearly 800 miles to Los Angeles and southern California from the wetter northern parts of the state. Outside of the United States, expensive desalination plants have been in operation for many years in the Virgin Islands, many Persian Gulf states, the West Indies, Libya, South Africa, and Israel.

Introduction to Desalination: Principles, Processes, and Calculations, First Edition. Louis Theodore and R. Ryan Dupont.

An obvious way to increase water availability is to recover fresh water from seawater or large underground stores of brackish water that are available in many arid regions, but that are generally not usable without significant treatment. Other options for increasing potable water supplies is to find ways to use the saline or brackish water for agriculture or other uses that can tolerate higher salinity levels, or to actively pursue water conservation measures to protect limited fresh water supplies that may be available.

This chapter introduces the reader to the general subject of global water supplies and water scarcity issues through a review of water availability and water sources, global water resources, global water resource issues, and the history of desalination. A series of illustrative examples are provided to highlight concepts presented throughout the chapter.

1.2 Water Availability and Water Sources

The water on the surface of the Earth can be found in eight distinct compartments which are shown in Table 1.1 along with how much of the Earth's total water budget each makes up. These eight compartments are more commonly organized into three distinct groupings. First, there is *surface water*, which includes oceans, lakes, rivers, seas, etc. In short, surface water is all forms of liquid water that lie on the surface of the Earth. The second grouping is *glacial and frozen water*. These are resources that are located on the surface; however, these resources are in frozen, long-term storage. Long-term storage is defined as water that has historically taken thousands of years to move through the water cycle. The third and final grouping is *groundwater*. This is the water that is found below the surface of the Earth in conditions where the percent saturation in soil

Table 1.1 Breakdown of the total water budget on the Earth.

Water compartment	% of Total Earth's water budget
Oceans	97.2
Frozen glacier water & other ice	2.15
Ground or subsurface water	0.61
Freshwater lakes	0.009
Inland seas	0.008
Soil moisture	0.005
Atmospheric water	0.001
Rivers and streams	0.001

pore water is 100% (Mullen 2021). The process known as the hydrologic, or *water cycle*, has played a crucial role in the formation and distribution of all water resources on Earth today. The water cycle is used to describe the constant circulation of water through its three phases of solid, liquid, and gas as it moves within the eight compartments making up the water resource pool on the Earth.

1.3 Global Water Resources

Usable water is the key to sustainable life. However, out of all the water on Earth today, it is estimated that only 2.5 to 3.0% is usable. That still is quite a large amount of water, considering the Earth's total global water supply is over 1.39 billion km^3. However, when one delves deeper into this estimated usable supply, it is found that a little over 0.3% of the usable water on Earth is easily accessible (Gleick 1996). This usable water is found in rivers, streams, lakes, and swamps. With the ease of access to these forms of usable water being so high, it is estimated that over 50% of the world's population lives within 3.0 km of these surface water sources (Kummu et al. 2011). The majority of the available water that is not considered easily accessible is found in ground or subsurface water in natural aquifers.

Natural aquifers are the most common forms of groundwater storage. Today, these natural aquifers are thought to hold roughly 34.2 million km^3 of total water. Out of these 34.2 million km^3 of water, it is estimated that close to 10.4 million km^3 of this water is usable (Gleick 1996). Since these aquifers are below the surface of the Earth, they do require the construction of wells for water recovery. These wells can range from tens to hundreds of feet deep, depending on where the water table is located. It is also important to note that these wells will generally require the installation of a pumping system to bring the water to surface. Table 1.2 provides a comparison between the total water on Earth to the amount that is both groundwater and fresh-groundwater.

Table 1.2 Fresh groundwater, total groundwater, and total global water resources.

Water source	Water volume, mi^3	Water volume, km^3	% of Total water resource	% of Total fresh water resource
Fresh groundwater	2,526,000	10,530,000	0.80	30.1
Total groundwater	5,614,000	23,400,000	1.7	
Total global water resource	332,500,000	1,386,000,000		

As small as the ratio of total volume of usable water to unusable water is in the world, there are still considerable amounts of usable water resources present among the seven continents. The amount of usable water on each continent can be divided among the three water categories as just described earlier, i.e. groundwater; glacier/permanent ice caps; and surface water (i.e. wetlands, lakes, reservoirs, and rivers). These categories, along with the volumes of water in each for each continent across the globe are summarized in Table 1.3.

On examining Table 1.3 it becomes immediately obvious that Antarctica has by far the largest amount of fresh water of any continent. However, this fresh water is in the form of glaciers and permeant ice caps, thus making it unusable. When comparing usable water resources, the top three continents are Asia, with roughly 7,830,622 km^3 of water, Africa, with approximately 5,531,776 $km^3$of water, and North America, with 4,327,003 km^3 of total usable water resources. Furthermore, these three continents contain over 75% of the usable water on Earth. With this large amount of water being contained in three of the seven continents, mankind has adapted through the development of artificial reservoirs. These artificial reservoirs are most commonly constructed by the creation of a dam around an existing natural water source. Today, it is estimated that there are more than 515,000 of these man-made reservoirs of greater than 2.5 ac in size that cover roughly 258,000 km^2 of the Earth's surface (Osborn 2019).

Table 1.4 summarizes the annual renewable fresh water resources for the top 25 countries in the world. Renewable fresh water resources are an estimate of the average precipitation, recharged groundwater, and fresh surface inflows

Table 1.3 Global water resources by continent (Modified from Rekacewicz 2006).

Continent	Glacier & permanent ice caps, km^3	Groundwater, km^3	Wetlands, large lakes, reservoirs & rivers, km^3	Totals, km^3	Total usable water resource, km^3
North America	90,000	4,300,000	27,003	4,427,003	4,327,003
South America	900	3,000,000	N/A	3,00,900	3,000,000
Europe	18,216	1,60,000	2,239	1.620,745	1,602,529
Africa	0	5,500,000	31,776	5,531,776	5,531,776
Australia	180	1,200,000	221	1,200,401	1,200,221
Asia	60,984	7,800,000	30,622	7,891,606	7,830,622
Antarctica	30,109,800	N/A	N/A	30,109,800	0

Table 1.4 Renewable annual fresh water resources for top 25 countries (Table 1.4 Advameg, Inc. 2010).

Rank	Country	Total fresh water renewable resource, km^3
1	Brazil	8,233
2	Russia	4,498
3	Canada	3,300
4	United States	3,069
5	Indonesia	2,838
6	China	2,830
7	Colombia	2,132
8	Peru	1,913
9	India	1,908
10	Democratic Republic of the Congo	1,283
11	Venezuela	1,233
12	Bangladesh	1,211
13	Burma	1,046
14	Chile	922
15	Vietnam	891
16	Republic of the Congo	832
17	Argentina	814
18	Papua New Guinea	801
19	Bolivia	622
20	Malaysia	580
21	Philippines	479
22	Cambodia	476
23	Mexico	457
24	Ecuador	432
25	Japan	430

from surrounding countries that each of these countries receives in any given year. What is interesting to note from these data is that despite a country having a great deal of renewable fresh water resources, water shortages and unequal distribution of resources can still take place. Consider Brazil, which tops the list with over 8,233 km^3 of renewable fresh water each year. Despite what would appear to be an abundance of fresh water, Brazil is experiencing a long-term water crisis caused by poor water infrastructure and water resource

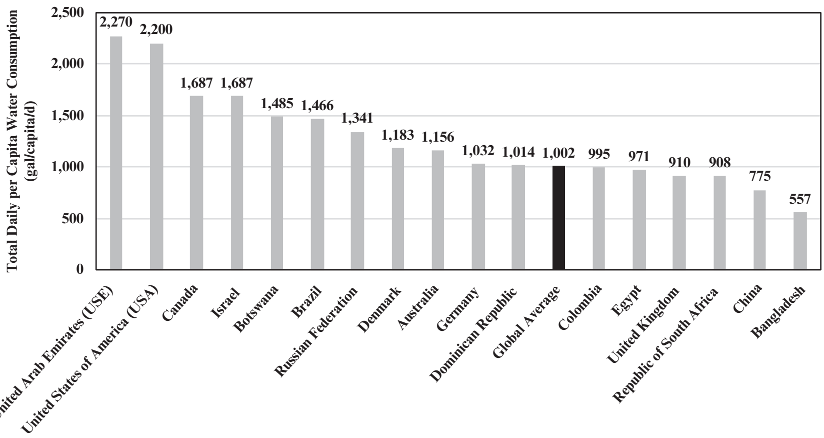

Figure 1.1 Total daily per capita water consumption by selected country. Data from Grace Communication Foundation (2019).

management which has left over 5 million, or more than 2% of its citizens without access to safe potable water (Water.org 2019).

Even in what is considered a highly advanced country like the United States, which receives 3,069 km^3 a year of renewable fresh water and has historically invested in water infrastructure as well as the management of its water resources, it is estimated that as of 2014, 1.6 million people (0.5% of its population) were without a toilet, a tub or shower, or running water (UNC Environmental Finance Center 2017). Despite availability of renewable fresh water resources, equitable and affordable supply and access to these resources remain a significant challenge, particularly to minority and low-income communities, even in the most developed countries in the world.

Figure 1.1 summarizes the total per capita water consumption (consumption of surface or groundwater for domestic, commercial and industrial purposes; water for crop production; and water required for the assimilation of pollutants produced from domestic, commercial, and industrial activities) for the select countries in the world whose daily consumption is above and below the global average (Mekonnen and Hoekstra 2011). The global average for total per capita daily water usage is roughly 1,000 gal/capita/d (Grace Communication Foundation 2019). This is water that is used for domestic purposes such as laundry, cooking, drinking, washing, etc., as well as water used for food production, and the production of consumer goods, like cars, plastic bags, clothing, etc. At the top of this list with 2,270 gal/capita/day is the United Arab Emirates, 76% of which is associated with products or ingredients of consumer goods imported annually into the UAE (virtual water). In the United States, of the 2,200 gal/capita/day of total water use, only 20% is associated with imported external water consumption. The significant differences seen in the daily internal versus external per capita total water consumption are directly attributed to the consumption habits of each country's citizenry.

1.4 Global Water Resource Issues

The root of all major issues pertaining to global water resources today stems from a lack of water accessibility. It is estimated that over 1 billion people live without access to safe water (WHO 2017). This number more than doubles to over 2.3 billion people when basic sanitation services are considered. It is this lack of access to safe drinking water and adequately treated wastewater that drives other major water-related issues in the world today. As indicated earlier, this access issue stems directly from the lack of necessary water infrastructure as well as the poor maintenance and management of the limited infrastructure that currently exists.

Improved water resource management and water storage capacity makes an economy more resilient to external shocks, such as rainfall variability, and thus provides a stable and sustainable base for increased food and industrial productivity and production to maintain economic growth and development. Consider a heavily water-dependent country like Kenya where frequent floods and droughts take a heavy toll on the economy (SIWI 2005). These floods and droughts translate to a direct long-term fiscal liability and decline in economic growth of about 2.4% of Kenya's annual GDP (SIWI 2005). Much of this loss in economic output comes from lack of adequate water storage capacity, a deficit of more than $10 billion in 2004 (SIWI 2005). If Kenya, as for many other African countries, had invested in storage facilities for water, they would be able to store the excess water received in heavy flood years for use in heavy drought years, thus, avoiding flood liabilities and water scarcity cost, allowing the country to avoid the drops in economic growth that have occurred in the past.

The SIWI (2005) indicated that national economies are more resilient to rainfall variability, and economic growth is increased when water storage capacity is improved. Investing in adequate water resource management in developing countries would be expected to produce significant economic gains of between two to four times the infrastructure investment. The SIWI (2005) concluded that an even greater return on investment of $8.00–$200 would be saved in water treatment costs for every $1.00 invested in watershed protection. Investments in improved water and sanitation infrastructure in developing countries also has significant economic benefits when considering increased productivity from the improved health of workers in households and the commercial and industrial sectors, ranging from hundreds of millions to billions of dollars annually (SIWI 2005).

In today's world, the term *hydro-politics* is becoming more and more known. Hydro-politics can be defined as debate or conflict amongst individuals, parties, or organizations within governments about water-related issues. These debates/conflicts may even take place between multiple countries, not just the individuals within those countries. Commonly, these types of conflicts are solved by establishing a system known as *Riparian Water Rights*. This is a system used to allocate water among different countries or jurisdictions within countries that are in control of the land through which the water travels. These types of rights are considered common law amongst many countries in the world such as the United States, Canada, Australia, and Great Britain.

Even though many of the largest countries in the world have used this system to manage water conflicts for years, there are many other countries where these systems are relatively new. A prime example of this is conflict between Egypt and Ethiopia. For centuries, these two countries have been in constant conflict over who owns the developmental rights for the water in the River Nile. It wasn't until 2015 that these two counties set aside their differences and signed an agreement ensuring shared and equitable access to the river (Lufkin 2017).

Even with compromises such as the one between Egypt and Ethiopia, some individuals, such as Ismail Serageldin (former Vice President of the World Bank), see water becoming the next so called "Oil War." Ismail Serageldin famously said, "The wars of this century were fought over oil, the wars of the next century will be fought over water" (Barnaby 2009). However, when one sees countries coming together to solve their water resources conflicts, forming compromises like Egypt and Ethiopia, the potential for water wars seem less likely, and the arguments by Barnaby (2009), Fröhlich (2012), and McCrary (2018) appear to have more validity. These latter authors believe that physical conflict over water will not happen because established systems for international trade and international agreements leading to mutual benefits ease these conflicts, thus preventing the scale of these problems from becoming large enough to cause military style confrontations. Certainly, the expansion of available water supplies through the expansion of desalination technologies will contribute to the reduction in multinational conflicts over water and ensure more adequate water supplies for all peoples.

1.5 History of Desalination

Three prime candidate desalination processes have emerged and are briefly reviewed in the sections to follow.

1.5.1 Evaporation Processes

The oldest and best developed process for saline water conversion is the evaporation (or what some define as distillation) method. While there are many desalination technologies in use or being developed today, desalination began using evaporative processes. These evaporative desalination techniques were recognized over 2,000 years ago when Aristotle wrote in 320 B.C., “saltwater, when it turns into vapor, becomes sweet and the vapor does not form saltwater again when it condenses.” Evaporation remains the major method today for commercial production of fresh water from seawater. In principle, evaporation is the simplest method. Seawater is boiled in an evaporator (Flynn et al. 2019; Theodore 2014; Theodore et al. 2017) by passing hot steam through a steam chest where the steam condenses on the inside of the tubes of the chest and is usually returned to the boiler. The vapors rising from the seawater feed are cooled in a condenser and thus converted into pure liquid water which is collected in a storage vessel. The resulting concentrated brine solution is continuously or intermittently withdrawn from the evaporator. The most advanced commercial evaporation processes are the following:

1. Multiple-Effect Evaporation.
2. Flash Evaporation.
3. Vapor Compression Evaporation.

Details of these processes are provided in Chapter 10.

1.5.2 Membrane Processes

Electrodialysis was the membrane separation process employed for desalination a century ago. Here, the ions forming the salt are removed from the saltwater by electric forces and concentrated in separate compartments. However, the higher the salinity of the raw water, the more electric power is needed for this process. Hence, this process was applied primarily in the treatment of moderately brackish waters containing 1,000 to 2,000 mg/L of dissolved salts. In recent years, reverse osmosis (RO) (Theodore and Ricci 2010) has displaced electrodialysis as the primary membrane separation desalination process, leaving the latter as the choice for medical kidney applications.

An RO system consists of an intake, a pre-treatment component, a high-pressure pump, a membrane apparatus, remineralization, and pH adjustment components, as well as a disinfection step. Generally, a pressure of about 1.7 to 6.9 MPa is required to overcome the osmotic pressure of saltwater.

This advanced separation technique may be used whenever low molecular weight solutes such as inorganic salts or small organic molecules (e.g. glucose) are to be separated from a solvent (usually water). In normal (as opposed to reverse) osmosis, water flows from a less concentrated salt solution to a more concentrated salt solution as a result of an innate concentration driving force (thermodynamically referred to as the chemical potential). As a result of the migration of water through the membrane, an "osmotic pressure" is created on the side of the membrane to which the water flows. In RO, the membrane is permeable to the solvent or water and relatively impermeable to the solute or salt. In order to make water pass through an RO membrane in the desired direction (i.e. away from a concentrated salt solution), a pressure must be applied that is *higher* than the osmotic pressure. The membranes used for RO processes are characterized by a high degree of semi-permeability, high water fluxes, good mechanical strength, chemical stability, and relatively low operating and capital costs. Early RO membranes were composed of cellulose acetate, but restrictions on process stream pressure, temperature, and organic solute rejection spurred the development of noncellulosic and composite material membranes ("sandwiches"). These membranes may be configured into a variety of geometries for system operation, including: plate and frame, tubular, spiral wound (composite), and hollow fiber.

1.5.3 Crystallization Processes

Crystallization processes were also employed over 2,000 years ago. Today, these processes are important mass transfer operations that are often employed in the preparation of a pure product. In the process, a crystal usually separates out as a substance of specific composition from a solution of varying composition. Any impurities in the liquid (often referred to as the mother liquor) are carried in the crystalline product only to the extent that they adhere to the surface or are occluded (retained) within the crystals that may have grown together during or after the crystallization operation. The separation of a solid from a solution onto a crystal occurs only if there is a state of imbalance involving a mass driving force; namely, a decrease in chemical potential (or concentration) between the bulk of the liquid solution and the crystal interface. This effectively means that the solution must be supersaturated. There are several different ways that crystallization can occur. The four most often encountered in practice are (Theodore 2014):

1. Cooling.
2. Evaporation.
3. Cooling and evaporation (also referred to as adiabatic evaporation).
4. A salting out process.

Process 1 is the most commonly employed, provided the solubility of the component being crystallized decreases with decreasing temperature.

World-wide development of desalination techniques in the last half century has been driven out of necessity due both to water scarcity and population growth. The private sector has primarily led the investment in research and development since water has begun to be seen not as a commodity, but as a product to be sold at a profit. This development by the private sector has led to a significant drop in the cost of water generated using these desalination techniques.

1.6 Summary Observations

The following summary observations can be made related to water, seawater desalination, and water treatment in general.

1. Water demand at both the national and international levels is increasing at a faster rate than originally realized.
2. Water demand at both the national and international levels is increasing at a faster rate than population growth.
3. There is indeed growing water scarcity.
4. One approach to solving this water scarcity problem is to develop and/or find new sources of water.
5. Nonconventional water sources will become more attractive in the future.
6. Water conservation measures should be expanded in the future.
7. Seawater and brackish groundwater are nonconventional water sources serving as feedstock for desalination processes.
8. Poor seawater quality can limit RO applications but generally does not have as great an effect on evaporation and crystallization processes.
9. Desalination processes featured evaporation in earlier times, while RO is generally the process of choice today.
10. The increasing demand for potable water will ensure that improvements in current technologies and development of new approaches for potable water production will continue to develop in the future.

1.7 Illustrative Examples

Five illustrative examples complement the material presented in this chapter.

1.7.1 Illustrative Example 1

Describe the role process water plays in industrial processes/applications.

Solution. Process industries rank above all others as users of water. No process plant could operate without water as a cooling medium and as a direct raw material in certain phases of a process. The local water supply, therefore, must be studied before an area can even be considered as a possible site for a processing facility. A detailed estimate of present and future water requirements must precede a plant siting study. Then the availability of water in the region being considered should be carefully investigated. If well water is to be used, a complete study of the history of the groundwater table is necessary. If groundwater supplies are adequate, they are preferred because of their lower temperature and generally higher water quality as compared to surface water sources.

Surface waters from streams or lakes also require careful consideration since both their quantity and quality can vary greatly on a seasonal basis. Streams discharging into the ocean during times of low runoff can become saline as a result of seawater intrusion. Under such conditions, plant design may have to include large storage facilities for fresh water to be collected during periods of high runoff and used during dry seasons when the stream becomes saline.

Companies moving into relatively nonindustrialized areas often fail to consider the possibility of other plants following suit. The availability of the water supply should be adequate not only for the future needs of the proposed plant but also for the anticipated needs of other industries that might move into the area. It is also desirable to consider alternate sources of supply that may be required if the preferred water source becomes depleted. Water quality must be studied as well as water quantity. Chemical and bacteriological examination will indicate the extent of treatment required and can aid in the development of water cost figures for comparison with other locations. The possible contamination of the water source by other industries in the area should be anticipated. Note that "contamination" may consist of raising the temperature of the water to a level that renders its use as a cooling medium impossible.

1.7.2 Illustrative Example 2

A range of water needs typically exist within a facility, all of which may have different water quality requirements for specific uses. Describe five of these common needs.

Solution. Five common industrial facility water uses include:

1. Cooling Water. Natural and forced-draft cooling towers are generally used to provide the cooling water required at a site unless water can be drawn from a convenient river or lake in sufficient quantity to meet a facility's cooling demands. Seawater or brackish water can be used at coastal sites but, if used directly, necessitates more expensive materials of construction

for heat exchangers because of potential corrosion problems resulting from the high dissolved solids content of this water. Often, this cooling water does not have to be of high purity and can be taken from blowdown streams from boilers or process lines that require much more stringent water quality conditions.

2. Potable and General Use Water. The water required for general purposes on a site is usually taken from a local municipal or private supplier, unless a cheaper source of suitable quality water (e.g. a river, lake, or well) is available. If the cost of this supply is low, incentives for water use reduction will also be low. It should be remembered, however, that the cost of the supply may be a small portion of the overall cost of managing this water, particularly if it is used in process rinsing, general facility cleaning and wash-down, etc. More water use requires more energy to convey it from the source and within a plant. When the water becomes contaminated, costs for its handling increase exponentially. In addition, waste treatment becomes progressively less efficient and more costly as a waste stream is diluted, and load penalties may be incurred based on the volume of waste discharged to publicly owned treatment works (POTWs). It should be evident, then, that numerous benefits can be associated with increased water use efficiency within a plant.
3. Demineralized Water. Water from which all the minerals have been removed by ion exchange must be used where ultrapure water is needed to meet process demands and strict boiler feedwater requirements. Mixed and multiple-bed ion exchange units are used for this purpose, with resins exchanging multivalent cations for hydrogen. Boiler water as condensed steam and process water must be removed on a routine basis (blow down) to prevent the build-up of unwanted constituents within these systems, and this ultrapure water may be effectively reused within a plant for other unit operations that demand much less stringent water quality characteristics, i.e., cooling water, process rinse water, and so on.
4. Refrigeration. Refrigeration is needed for processes that require temperatures below those that can be economically obtained with cooling water. Chilled water can be used to lower process temperatures down to approximately 10°C. For lower temperatures, to -30°C, salt brines (NaCl and $CaCl_2$) are used to distribute the “refrigeration” around the site from a central refrigeration unit. Vapor compression machines are normally used for this purpose. As with boilers, evaluation of the operating conditions of a chiller can lead to significant pollution prevention opportunities. Consider, for example, that a 1% improvement in chiller efficiency can be expected for each 1°F increase in the chiller set point.
5. Steam. The steam for process heating is generated in either fire - or water-tube boilers, using the most economical fuel available. The process temperatures required can usually be obtained with low-pressure steam

(typically 25 psig), with higher steam pressures needed only for high process temperature requirements. A significant pollution prevention, energy conservation, and cost reduction opportunity may exist in a facility's steam generation system, as many facilities operate at higher than necessary steam pressures, increasing their energy demands for steam production and the cost of producing this steam. In addition, repair and replacement of leaking steam and condenser lines will prevent the wasting of steam and the associated energy and cost needed to produce this wasted steam.

1.7.3 Illustrative Example 3

Briefly describe the wastewater streams typically generated in the petroleum industry.

Solution. Throughout the life cycle of crude oil, through extraction, transportation, and refining, roughly 5 to 7 gal of water are used for every 1 gal of crude oil processed. Of this total, roughly l to 2.5 gal of water are used for every 1 gal of crude oil stock. In the United States, 1 to 2 billion gal of water are used per day in the refining industry. Water consumption varies for different regions and different qualities of crude oil. These water estimates do not include unconventional shale formations, where water usage is generally much higher. Water consumption in refining is a result of evaporation and drilling, blowdown, process discharge, and some incorporation into finished products. All water that is incorporated into the refining process is treated or filtered onsite before it is either reused on site or discharged into the environment.

Wastewater streams include separation process wastewater, tank bottoms, cooling tower condensate blowdown, source water treatment, and storm water. American Petroleum Institute (API) separators are commonplace in most refineries and separate sludge and hydrocarbon components out of process wastewater. Refineries today have installed dike systems to keep process wastewater from draining into storm sewers.

1.7.4 Illustrative Example 4

Refer to Table 1.5 and calculate the desalination mass capture efficiency of salt in seawater to convert typical seawater to potable water. Assume a basis of 100 g of seawater.

Solution. For 100 g of seawater,

Salt in seawater = 3.5 g

Salt in potable water = 0.05 g

The required salt capture efficiency, *SCE*, is therefore:

$$SCE = \frac{(3.5 - 0.05)}{3.5}(100) = 98.6\%$$

1.7.5 Illustrative Example 5

Mekonnen and Hoekstra (2011) provide a summary of national water footprints of production and consumption for countries around the world. They provide a guideline for the determination of the representative water footprint of various commodities that may be both produced within a country as well as imported for consumption from elsewhere around the globe. An example that is provided determines the average water footprint for tomatoes consumed in Germany. Using the data presented in Table 1.6, determine what the water footprint for tomato consumption in Germany is assuming the total quantity imported is consumed, using a weighted average of each water footprint for tomatoes imported from other countries.

Solution. Using a weighted average of the water footprint and Germany's import levels from the countries listed in Table 1.6 yields the following results using Equation 1.1 for the calculations.

$$\text{Water Footprint} = \frac{\int_1^n (\text{Tomato Consumption, T/yr})_i (\text{Water Footprint, } \text{m}^3/\text{T})_i}{\text{Total Tomato Consumption, T/yr}} \tag{1.1}$$

where Tomato Consumption = annual T of tomatoes produced or imported and consumed from each country, i; Water Footprint = m^3 water/T tomatoes produced from each country, i; and n = total number of countries, including itself, from which Germany imports tomatoes. Substituting values from Table 1.6 into Equation 1.1 yields:

$$\text{Water Footprint} = \frac{(47{,}000)}{(36) + (252{,}000)(10) + (244{,}000)(83) + (72{,}000)(109) + (52{,}000)(110)(\text{T/yr})(\text{m}^3/\text{T})(667{,}000\,\text{T/yr})}$$

$$\text{Water Footprint} = \frac{38{,}032{,}000}{667{,}000} = 57\text{m}^3/\text{T}$$

Table 1.5 Seawater and potable water major components.

	H_2O, wt%	Salt, wt%
Seawater	96.5	3.5
Potable water	≥99.95	≤0.05

Table 1.6 Water footprint and quantities of German tomato consumption as a function of place of origin.

Place of origin	Quantity imported or consumed, T/yr	Water footprint, m^3/T
Germany	47,000	36
The Netherlands	252,000	10
Spain	244,000	83
Italy	72,000	109
France	52,000	110
Total	667,000	

1.8 Problems

1. In terms of the question "how much water is there?" explain why only approximately 0.3% of the entire water on the Earth is considered usable fresh water.
2. With so much water on the planet explain why there is a water availability and water supply crisis.
3. List and briefly describe the four major aquatic habitats in the United States and indicate concerns regarding contamination of these resources.
4. SIWI (2005) and Hares (2017) have made strong cases for the economic benefit of water infrastructure investments around the world. In the United States, the US Water Alliance (2017) outlined the way forward for ensuring all people have access to clean, affordable water, and all benefits from water infrastructure investments to make water supplies more reliable and resilient in the face of climate change pressures. Review the US Water Alliance (2017) national briefing paper on water equity and summarize the "Three Pillars" of water equity put forth in this document.
5. A comparison of global drinking water supply and sanitation services provided by WHO (2017) suggests that in 2015, North America had some of the highest rates of improved water supplies (96%) and basic sanitation (97%) and safely managed improved sanitation facilities (78%) in the world. The statistics for the United States are even higher at 99% of the population using improved water supplies, while 89% were using improved sanitation facilities. For those in the United States either not having access to improved water supplies or improved sanitation facilities, UNC Environmental Finance Center (2017) has indicated that conditions for them are similar to individuals in developing countries. Review the UNC

Environmental Finance Center (2017) document on *Clean Water Access Challenges in the United States* and summarize the six major clean water access challenges they identified in twenty-first-century America.

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