FUNDAMENTALS OF WATER SECURITY

QUANTITY, QUALITY, AND EQUITY IN A CHANGING CLIMATE

JIM F. CHAMBERLAIN
DAVID A. SABATINI

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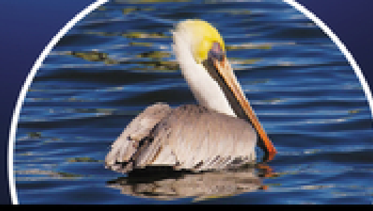

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Quantity, Quality, and Equity in a Changing Climate

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The authors dedicate this work to:

> *My students who inspire me with their passion for the world's most disadvantaged peoples, and my brother-in-law, Frank Zemanek, who paddled with me many peaceful and beautiful waters.*
>
> *(Jim)*
>
> *My wife - Frances Sabatini - and my children and their families - Caleb, Kirbie and Conrad Sabatini, and Peggy and Hunter McDonald - for their love, encouragement, and endearing support.*
>
> *(Dave)*

Contents

Preface

The world is rapidly changing. Burgeoning populations along with ever-increasing standards of living, especially for those in emerging countries, increase the *demand* and stress on our water resources. What is not increasing, however, is the *supply*, the total amount of water in earth's biosphere, water that is integral to all standards of living. This water is needed not only for human consumption and growing the food we eat but also for generating electricity, for sustaining health and healing illnesses, for maintaining ecosystem services, and for making various other products and services that comprise life's modern amenities. No less importantly, water has been, and continues to be, used for transportation, recreation, cultural well-being, and religious ceremony. Water, thus, is valuable from physical, cultural, and spiritual vantage points. While the total amount of water remains the same, the amount that is available and useful at any given time and place, for human and ecological flourishing, is transitory between its various stocks and flows.

Water security is the modern term that describes a state of having sufficient quantity and quality of water necessary to equitably meet both immediate and long-term human and ecological needs. As such, water security spans multiple environmental science and engineering disciplines, including groundwater and surface-water hydrology, geography, geology, water resources, soil science, ecology, atmospheric science, chemistry, biology, and health science, and also the disciplines of social and political science.

This volume is an introductory volume directed toward both the academic student and the practitioner. As a textbook, this volume could be used for the education of upper-level undergraduate or entry-level graduate students who already have some background in chemistry, biology, and mathematics. For the practitioner, this volume serves as an introduction to the diverse field of water security, perhaps serving as a supplement to critical hands-on training and experience.

In the **Introduction (Part I)** section, we begin by defining water security as existing at the water quantity–quality–equity nexus along with a brief overview of historical water challenges and insecurity and the manner in which affected communities adapted. The second section of the book – **The Context of Water Security (Part II)** – offers basic principles of water security under the threefold headings of water quantity, quality, and equity. Here, the student is given a basic understanding of hydrology, watershed management, aquatic chemistry and biology, and the social dynamics of water access and distribution. The final chapter in this section is devoted to climate change, which impacts all three of these principles. The third section – **Competing Uses of Water and Threats to Security (Part III)** – delves deeper into the diverse uses of water – for food, energy, industry, and ecosystems – and security threats that exist within, and at the nexus of, these uses.

The fourth section, entitled **Sustainable Responses and Solutions (Part IV)**, presents modern attempts to correct and/or mitigate the challenges of global water stress in pursuit of water security. The final section – **Resilience, Economics, and Ethics (Part V)** – invites the reader to consider various approaches to water planning as well as the fundamentals of water resource economics, critically important to water security. Finally, we propose an ethic of water for the modern pilgrim.

Case studies and examples are given throughout the text in order to both illustrate the principles and to create a sense of solidarity with sisters and brothers throughout the world. Regions in both developed and developing countries are now, or will soon be, experiencing water stress, and so we include issues and examples from a range of global contexts. We also highlight seven persons who have been working in various aspects of water security in sections called **The Practice of Water Security** following several chapters. These women and men are winners of the University of Oklahoma International Water Prize, awarded biennially from 2009 to 2022. Finally, most chapters culminate in a "Foundations" section, which provides a more quantitative probe into the science of water security. Depending on the background and orientation of the reader or student, this section may be considered optional.

The study of water security can be both sobering and optimistic. Because water is most often experienced as a local resource, there are "haves" and "have-nots" in the world of water security. But there are also signs of a brighter future – from a greater application of old and new technologies, a growing appreciation for the benefits and vulnerability of our water resources. and a desire for water cooperation and innovation among diverse entities.

Acknowledgments

This book began with material developed for two University of Oklahoma courses – an on-campus course “Introduction to Water” (taught by Chamberlain) and a new “Water Security” course (taught by Sabatini) developed as part of our online Master’s program in *Hydrology and Water Security*. We would like to acknowledge those students who provided helpful input into both courses based on their particular knowledge and experience. We especially thank Christian Newkirk, Heath Orcutt and Shannon Mathers for their assistance in the tedious work of producing figures as well as gaining permission for the use of existing figures. Their contributions are felt – and seen – throughout this book. We would also like to acknowledge the School of Civil Engineering and Environmental Science (CEES), the Gallogly College of Engineering, and the University of Oklahoma administration for their support of our efforts, which are an outgrowth of the OU WaTER Center, the Hydrology and Water Security program, and the larger water enterprise on campus. Without their support, and invaluable interactions with our esteemed colleagues, this volume would not have been possible.

We want to thank the many academic colleagues from across the US that provided valuable input into the content of the above courses and the outline of this book. Their input was invaluable. We also want to thank water experts that provided detailed reviews of specific chapters – Drs Emma Colven, Randy Kolar, R. David Lamie, Mark Shafer, Aondover Tarhule, Evan Tromble, and Paul Weckler – and a very special thanks to Dr. Michael Campana, affectionately known as Aquadoc (Doctor Water), for reviewing the book draft in its entirety.

Finally, we give thanks to our generous and passionate colleagues, the Directors of the OU WaTER Center – Drs Yang Hong, Robert Knox, Robert Nairn, Jason Vogel and, especially, Randy Kolar, who continue to lead us and inspire us to do great work on behalf of the common good.

About the Companion Website

This book is accompanied by a companion website.

www.wiley.com/go/chamberlain/fundamentalsofwatersecurity

This website includes solutions to selected end-of-chapter problems.

Part I

Introduction

1

Introduction to Water Security

In this chapter, readers are introduced to the concept and importance of global water security. Many of the United Nations Sustainable Development Goals address or depend upon water security. Several water-security definitions are presented with a brief discussion on the focus and limitations of each. We then offer a network of considerations that form the context for water security – water quantity, quality, and social equity. In the context of these three components, water security is found at the nexus where water is of suitable quality for the user's purpose(s), is of sufficient quantity for the user's purpose(s), and is equitably available to users, regardless of age, gender, social, or economic status. And all of this happens in the modern setting of a changing climate. The chapter then discusses various ways in which water security is measured, using metrics that are quantifiable and useful for comparison. The analysis of water security can be at watershed, household (local), regional, or global level for bases of comparison.

Learning Objectives

Upon completion of this chapter, the student will be able to:

1. Understand the concept of global water security with its various facets and components.
2. Articulate a working definition of water security.
3. Discuss the ways in which many of the United Nations Sustainable Development Goals, either directly or indirectly, overlap with water security.
4. Quantify water security using several commonly used metrics.
5. Understand the various scales of water security – from local to global.
6. *Utilize the various units of measurements of water quantity and quality.

1.1 Introduction

What do we think of when we hear the term **"water security"**? We might immediately think of water that is needed to survive, to live. This is the water that we drink to sustain our bodily functions. Water is necessary for all biochemical processes, as reflected by the fact that our bodies are composed of 60% water (Ford 2016). But water is also needed to grow food, from

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cabbage to cow and everything in between. We might next think of the other ways that we use water in the home – for cooking, cleaning, bathing, and watering plants and landscape. Water security then would involve the availability of enough water to accomplish these very personal tasks upon which we all depend.

But as our horizons expand a bit, we might also realize that populations historically tended to settle near bodies of water, along rivers, lakes, seas, springs (fed by groundwater), and coastlines. This early development reflects the fact that water is necessary for sustaining agriculture, for transporting goods, for power generation, and for supplying the industrial sector that undergirds a nation's economy. Thus, water security is not only a local phenomenon but also a regional and global one. Whole populations can be affected by drought, by flooding, and by widespread contamination that threatens the quality of a large water body. Whole segments of a population may also lack access to water of sufficient quality and quantity. This lack of access may be because they cannot afford to purchase water or because they are unfairly prevented from accessing a water source. These examples foretell the inverse of water security, that is, the *in*security that comes with an imbalance of water quantity, a degradation of water quality, or water inequity that results in an inability to access the water necessary to sustain life.

These initial thoughts lead us to realize that *water security* is a consequence of scale, focus, and function. The *scale* of water security may be local (household), regional (watershed, aquifer), national, transboundary (within or between countries or other jurisdictions), or global. The *focus* of water security may be on the quantity, quality, or equitable access (equity) to water. The *function* of water security may be on basic human health and wellbeing, economic progress, ecosystems' functioning, or any combination of the above. These aspects are captured in the four editorial foci for the journal *Water Security* (Lall et al. 2017):

- Shortage (water quantity)
- Flooding (water quantity)
- Governance (water equity)
- Health and sanitation (water quality)

Likewise, a threat to water security (i.e. the threat of water *in*security) will also be faced, analyzed, and mitigated according to water quantity, quality, and equity, which are all intertwined. The lack of quality, quantity, or equity represents an uneven risk to people, the economy, and/or the environment. And so, a drought that threatens the Ethiopian teff harvest may affect rural people to a greater extent than city dwellers who have a more diversified diet. The construction of a Tennessee dam that generates hydroelectric power for local benefit may upset aquatic ecosystems downstream in neighboring states. The Bangladeshi reliance on groundwater wells to avoid cholera-impacted surface water may expose unsuspecting villagers to water tainted with arsenic. In addition, nearly all of these threats will be impacted by a climate that is warming gradually and consistently.

In this introductory chapter, we describe both the measures and usefulness of water security as a basis for study and analysis. Subsequent chapters will zoom in on various foci within the areas of water quantity, quality, equity, and climate change while looking at water security at a number of scales.

1.2 Sustainable Development Goals (SDGs)

Adopted in 2015, the United Nations **Sustainable Development Goals** (SDGs) set forth 17 targets (endpoints) designed to achieve a better and more sustainable future for all peoples (United Nations 2015) (Figure 1.1). One of these goals specifically addresses "Clean Water and Sanitation" (SDG 6). The goal of SDG 6 is to "Ensure availability and sustainable management of water and sanitation for all." This goal will be achieved by, among other things, reducing water pollution, increasing water-use efficiency, protecting ecosystems and watersheds, and strengthening proper water management (Table 1.1).

Other SDGs are also intertwined with water security (United Nations 2015). Table 1.1 illustrates the connections between water and several of the SDGs. Water is needed to grow food and put an end to hunger (SDG 2). Clean water is needed for the elimination of waterborne diseases (SDG 3). Children must be regularly healthy in order to attain a quality education (SDG 4). The need for women and girls to fetch water at long distances is a threat to their safety and ability to attend school along with the boys. Such is a deterrent to gender equity (SDG 5). Water-related disasters result in economic losses that are much harder on the poor and vulnerable in urban settings (SDG 11). Water safety entails the proper management of chemicals that might be released into the hydrosphere (SDG 12), and the cooperation of international bodies is required to protect terrestrial and inland freshwater ecosystems and their services (SDG 15). In order to meet these goals, stakeholders will need to use the basic tools of water security, including knowledge of hydrology, integrated

Figure 1.1 Seventeen Sustainable Development Goals (SDGs) agreed upon by member states of the United Nations, ushered in on 1 January 2016 (Martin 2015). Source: With permission from United Nations.

Table 1.1 Sustainable development goals (SDGs) and targets that are directly and indirectly relevant to water security.

<table>
<tr><th colspan="2">SDGs DIRECTLY RELEVANT TO WATER SECURITY</th></tr>
<tr><td colspan="2">SDG 6: “Ensure availability and sustainable management of water and sanitation for all”

6.1 Achieve universal and equitable access to safe and affordable drinking water for all.
6.2 Achieve access to adequate and equitable sanitation and hygiene for all.
6.3 Improve water quality by reducing pollution.
6.4 Increase water-use efficiency across all sectors and reduce the number of people suffering from water scarcity.
6.5 Implement integrated water resources management at all levels.
6.6 Protect and restore water-related ecosystems.
6.A Expand international cooperation and capacity-building support to developing countries.
6.B Strengthen the participation of local communities for improving water and sanitation management.</td></tr>
<tr><th colspan="2">SDGs INDIRECTLY RELEVANT TO WATER SECURITY</th></tr>
<tr><td>SDG 2: “End hunger, achieve food security and improved nutrition and promote sustainable agriculture.”

2.1 End hunger and ensure access by all people, in particular the poor and people in vulnerable situations … to safe, nutritious and sufficient food all year round.
2.2 End all forms of malnutrition … and address the nutritional needs of adolescent girls, pregnant and lactating women and older persons.
2.3 Double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers.
SDG 4: “Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.”

4.5 Eliminate gender disparities in education and ensure equal access to all levels of education and vocational training for the vulnerable, including persons with disabilities, indigenous peoples and children in vulnerable situations.</td><td>SDG 3: “Ensure healthy lives and promote well-being for all at all ages”

3.3 End the epidemics of AIDS, tuberculosis, malaria, and neglected tropical diseases.
3.9 Substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution and contamination.

SDG 5: “Achieve gender equality and empower all women and girls.”

5.2 Eliminate all forms of violence against all women and girls in the public and private spheres.</td></tr>
<tr><td>SDG 11: “Make cities and human settlements inclusive, safe, resilient and sustainable.”

11.5 Significantly reduce the number of deaths and the number of people affected … decrease the direct economic losses relative to global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations.</td><td>SDG 12: “Ensure sustainable consumption and production patterns.”

12.4 Achieve environmentally sound management of chemicals and all wastes throughout their life cycle … and significantly reduce their release to air, water and soil to minimize their adverse impacts on human health and the environment.</td></tr>
</table>

Table 1.1 (Continued)

SDGs INDIRECTLY RELEVANT TO WATER SECURITY	
SDG 15: "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss." 15.1 Ensure conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains, and drylands, in line with obligations under international agreements; 15.8 significantly reduce the impact of invasive alien species on land and water ecosystems, and control or eradicate the priority species.	

Source: United Nations (2015).

water management, and the food–energy–water nexus, to achieve the future envisioned by the SDGs.

1.3 Definitions of Water Security

The above discussion refers to water security without yet providing a definition of water security. The Global Water Partnership (GWP) has offered a very straightforward goal of water security, in which "every person has access to enough safe water at an affordable cost to lead a clean, healthy and productive life, while ensuring that the natural environment is protected and enhanced" (Lankford et al. 2013). Water quantity ("enough") and quality ("safe") are explicit in this definition while equity is implicit, using affordability as a surrogate.

Another practical definition is similar: "Water security is a condition in which there is a sufficient quantity of water, at a fair price, and at a quality necessary to meet short and long term human needs to protect their health, safety, welfare, and productive capacity at the local, regional, state, and national levels." (Kaplowitz and Witter 2002; Lankford et al. 2013). This definition reminds us that there are various levels to be considered, from local to national, and even international.

The United Nations gives an even more comprehensive definition of water security – "The capacity of a population to safeguard sustainable access to adequate quantities of and acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water related disasters, and for preserving ecosystems in a climate of peace (equity) and political stability." (United Nations 2013). This definition is robust because it encompasses water quantity, quality, and equity while also acknowledging the threats that water brings in the form of pollution and disasters, such as flooding. It also presents several of water security's outcomes, including human well-being, socioeconomic development, ecosystem preservation, and peace and political stability.

Figure 1.2 is a word cloud made from nine definitions of "water security" found in the literature. This word cloud highlights several key themes – quality, access, availability, acceptability, and ecosystem. Based on the above, and for the purposes of this text, we generate an operative definition of water security that is a slight modification to one given by Grey and Sadoff (Grey and Sadoff 2007).

Figure 1.2 Word cloud made from nine definitions of water security. Source: Author original (using Appelgren 1997; GWP 2000; Kaplowitz and Witter 2002; WHO 2003; Xia et al. 2006; Grey and Sadoff 2007; Calow et al. 2010; ADB 2011; Norman et al. 2011).

Water security is the equitable availability of a suitable quantity and quality of water for health and well-being, with an acceptable level of water-related risks to people, environment, and economies.

This definition encompasses scale, focus, and function while also acknowledging the reality that water itself brings risk to communities and the environment in which we live. The quality needed will depend upon the use of the water, and equity includes both access and affordability, which varies across nations and peoples.

1.4 Water Security at the Nexus of Quantity, Quality, and Equity

As is now becoming evident, water security develops at the nexus of the appropriate balance of water quantity, quality, and equity (Figure 1.3). This balance includes the minimization of unacceptable risks due to an overabundance (flooding) or lack (drought) of water, natural or manmade water pollution, and physical, societal, or political limitations to water access.

With regard to water, equity can be defined as the just and appropriate accessibility to sufficient water resources across gender, socioeconomic, spatial, and generational differences. For example, water resources are *not* equitable when:

- Women bear an inordinate burden of household water management, thereby limiting their education and development, when such a burden can be corrected

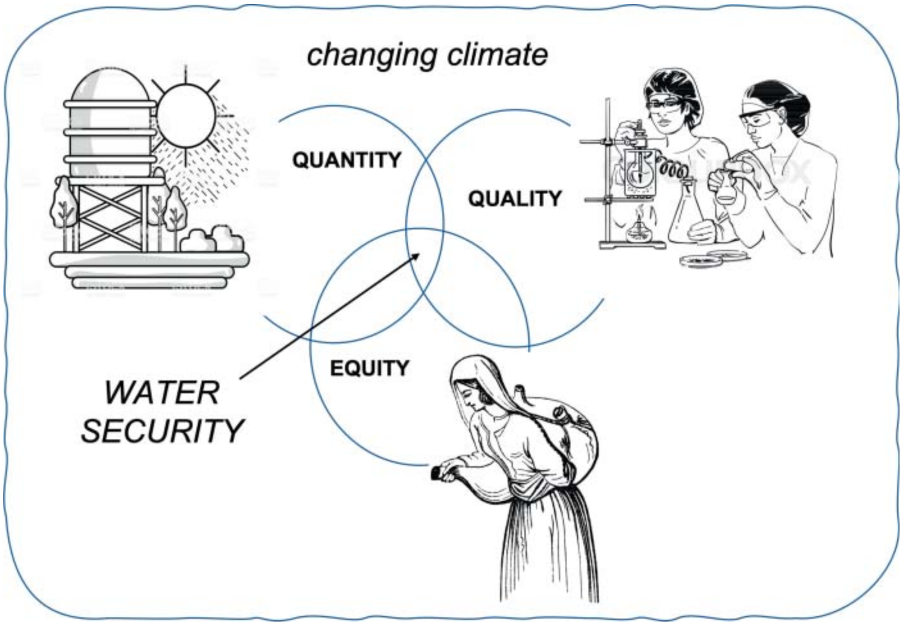

Figure 1.3 Water security is found at the nexus of the appropriate water quantity, quality for purpose, and equitable access, all in the context of a changing climate. Source: JFC author original.

- The price of water is beyond the reach of a typical household
- Rural villagers are excluded from water provision and management when such exclusion can be corrected
- An upstream entity uses an inordinate amount of water resulting in a lack of water security to an entity downstream
- An upstream entity releases a waste stream resulting in a degradation in water quality to an entity downstream
- The current generation is consuming fresh water at a rate that places a heavy burden on successive generations, as in the case of aquifer depletion.

A simple example here can be used to illustrate the water-security nexus of water quantity, quality, and equity. **Managed aquifer recharge** (MAR) in India can be accomplished by constructing small check dams across rivers or streams. In addition to storing water underground, where evaporation is limited or nonexistent, or replenishing the existing water in the subsurface rocks and sediments (aquifer), this practice has also been shown to improve water quality by reducing salinity levels as well as fluoride and arsenic concentrations in the groundwater. The improvement in quantity and quality makes this water more available for drinking or irrigation. But the practice is not as widespread as one might think given its obvious benefits. Stakeholders tend to be both wary of the intentions of central government (which funds or subsidizes the capital costs) and concerned about future maintenance issues and the control of quality of water entering the aquifer (Gunda et al. 2019). Water rights can also be an issue. Water security happens when local political and social conditions are favorable and supportive.

The benefits of water security are illustrated in Figure 1.4. The "bottom billion" are citizens of the 50 poorest nations, representing a population of about one billion, most of whom live

Figure 1.4 The "bottom billion" can reach the final goals of education and a firm economy only through climbing the prior "rungs" of water, sanitation, and health. Source: DAS author original; adapted from Living Water International.

on less than \$1 a day (Collier 2008). Each rung of the ladder of development enables them to reach an acquired benefit: water and sanitation lead to better health, better health improves the chances of acquiring a good education, and a good education allows one to contribute more fully to a stable economy while achieving a higher standard of living (e.g. food, access to medical care). The final outcome of this development ladder is hopefully a more stable society, a more peaceful world.

1.5 Metrics for Quantification and Comparison

In order to both evaluate water security and compare across populations, certain quantifiable measures have been found useful. This section describes some of the more common metrics.

- *Water stress and scarcity*. One common measure (and the simplest to calculate) is based on population and renewable water resources available on an annual basis. Using this measure, **water stress** is defined as water supply at or below 1700 m^3 of available water per person per year and **water scarcity** is supply at or below 1000 m^3 per person per year. *Absolute water scarcity* is applied to countries with less than 500 m^3/cap-year or roughly 1400 l/day per person, for all uses. By this definition, 49 countries are water stressed, 9 of which experience water scarcity and 21 experience absolute water scarcity (Table 1.2). By 2025, 1.8 billion people could be living in absolute water scarcity (United Nations 2013; Ford 2016).
- *SDG water withdrawal intensity (WWI)*. The SDG 6.4.2 (UN SDGs) uses a slightly different indicator of water stress. This indicator tracks the portion (%) of freshwater being withdrawn by all economic activities, compared to the total actual renewable freshwater resources (TARWR) available when flow needed for ecosystem services is safeguarded.
  As an equation,

$$\text{WWI}\,(\%) = 100 \times \frac{\text{Total freshwater withdrawal}}{[\text{TARWR}-\text{Environmental flow requirements}]} \quad (1.1)$$

Table 1.2 Examples of countries that are categorized as experiencing water stress, water scarcity, or absolute water scarcity.

Absolute water scarcity ($< 500\,m^3$/cap)	Water scarcity ($500–999\,m^3$/cap)	Water stress ($1000–1699\,m^3$/cap)
Algeria	Morocco	Poland
Libya	Egypt	Nigeria
Saudi Arabia	Sudan	Ethiopia
China (northeast regions)	Kenya	India
	South Africa	Pakistan
	Morocco	Belgium
	Burkina Faso	Czech Republic

Source: Black (2016).

In this equation, the numerator includes water withdrawals by all economic activities, with a focus on agriculture, manufacturing, electricity, and water collection, treatment, and supply [(UN-Water 2021), AQUASTAT database]. The denominator includes an accounting of surface and groundwater inflows, surface runoff, and treaty obligations and environmental flow as needed (United Nations 2020).

This metric provides an estimate of pressure by all economic activities on the country's renewable freshwater resources, directly responding to the environmental component of the target – "to ensure *sustainable* withdrawals and supply of freshwater." For example, Egypt had a WWI level of 117% in 2017, suggesting that it had overdrawn its freshwater resources by 17% (Figure 1.5). Algeria recorded a WWI level of 138% whereas the countries of India and South Africa had WWIs of 66 and 62%. Using this metric, many nations are withdrawing freshwater at a rate that is not sustainable.

- *Water poverty index (WPI)*. A third metric is the WPI, which produces a composite variable composed of five components that can be quantified: (i) access to water (Access); (ii) water resource quantity, quality, and variability (Resource); (iii) water uses by sector (domestic, food, productive purposes) (Use); (iv) capacity for water management (Capacity); and (v) environmental aspects (Environment) (Sullivan et al. 2003; Mason 2013). Each of the five components is weighted by experts and used for evaluating specific sites or regions. The components may, of course, be weighted equally, and a component may be omitted due to lack of data. The WPI can be used to compare communities, and those with a low index may be prioritized for attention.

$$\mathrm{WPI} = \frac{w_\mathrm{A}A + w_\mathrm{R}R + w_\mathrm{U}U + w_\mathrm{C}C + w_\mathrm{E}E}{w_\mathrm{A} + w_\mathrm{R} + w_\mathrm{U} + w_\mathrm{C} + w_\mathrm{E}}$$

where "A, R, …." are the quantities assigned to each component: access, resource, use, capacity, and environment, respectively, and "w_A, w_R, …." are the weights given to access, resource, use, capacity, and environment, respectively.

For example, a comparison of WPI was made for a large rural town in each of the three countries of South Africa, Tanzania, and Sri Lanka. In this case, each of the five components was given equal weight. The resulting WPIs are given as 43.1 (South Africa),

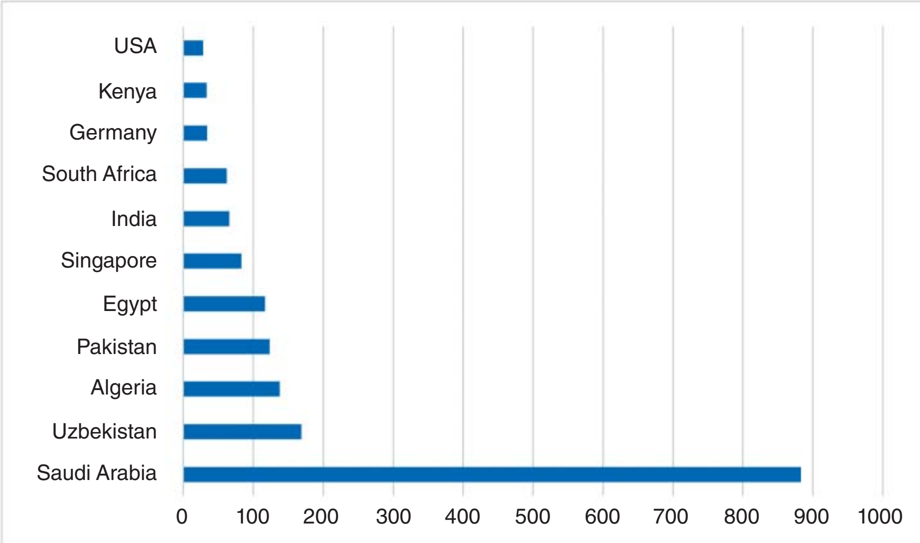

Figure 1.5 Water withdrawal intensity (WWI) for selected countries. Source: Based on United Nations (2020).

52.8 (Tanzania), and 46.4 (Sri Lanka). Figure 1.6 illustrates the comparison for three rural towns. The village in Tanzania scored high for "Environment," reflecting an awareness and wise use of natural resources and little degradation in the relevant watershed(s). The South African village scored high in surface water and groundwater availability and quality ("Resources"). Finally, the Sri Lankan village scored the highest in the "Use" category, which illustrates a more sustainable balance among domestic, livestock, agricultural, and industrial users.

- *Aqueduct water risk atlas*. The World Resources Institute (WRI) calculates water risk using water withdrawals, availability, and groundwater levels [see Dormido (2019) for more details]. Figure 1.7 highlights the countries that show extremely high risk (ExHR). The number indicates a country ranking, with Qatar (#1) as the country with the highest level of water risk. Note that this map does not reveal the regions within a country that could vary by risk. In addition, less obvious are the numbers of peoples that fall into the highest risk category. India has a population of 1.4 billion, more than all the other ExHR countries combined. Pakistan and Iran together have 287 million residents and the remaining ExHR countries comprise 102 million people.

Each of these metrics has its own advantages and limitations. Many of them depend upon accurate current data, which are often difficult to obtain. While care must be taken to make comparisons with these qualifications in mind, these metrics do have the advantage of providing a rough quantitative basis for prioritization and decision-making. They also alert us to the global nature of water security.

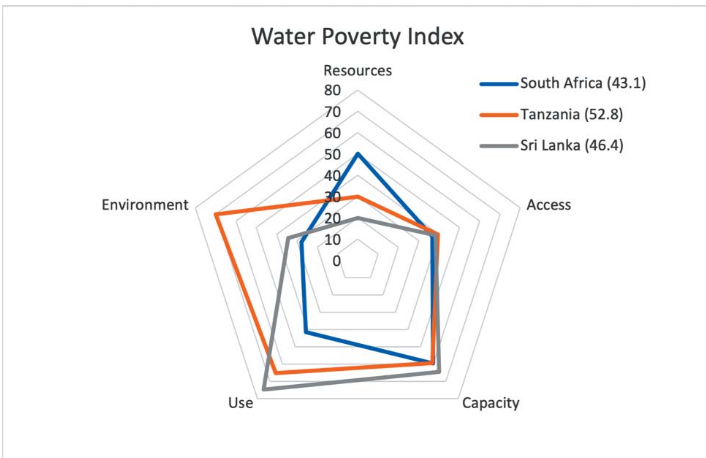

Figure 1.6 Water poverty index (WPI) determination for three countries, rural setting. A region with a higher score is considered more water-secure. Source: Original adapted from Sullivan et al. (2003).

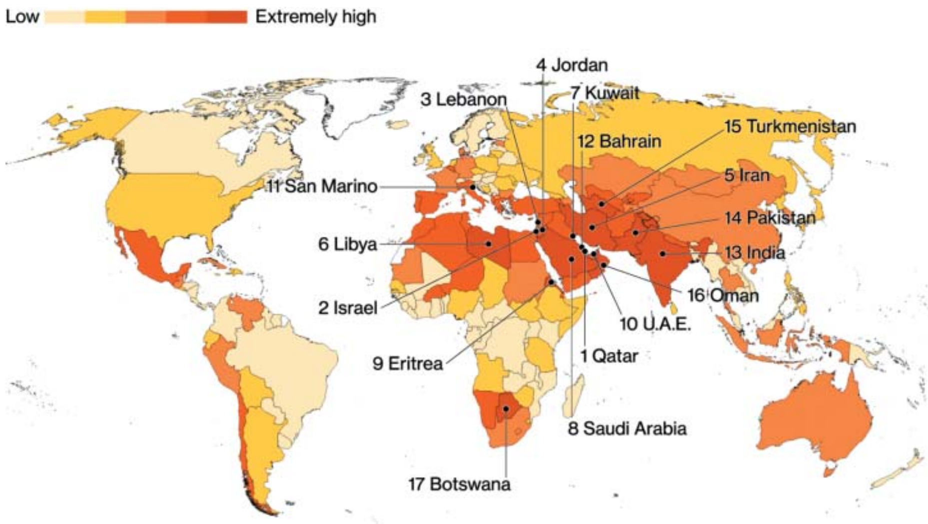

Figure 1.7 Baseline water-stress analysis using data on water withdrawal, and available water and groundwater for the year 2013. Source: World Resources Institute's Aqueduct Water Risk Atlas (Dormido 2019)/with permission from World Resource Institute.

1.6 Watershed Protection – Integrated Water Resources Management

Rain and subsequent runoff do not follow the political boundaries of a state or nation any more than birds do as they migrate south each Fall from their North American habitats. A watershed is an areal extent of land in which all precipitation falling on the land is channeled to a single outfall. That outfall might be a river, reservoir, bay, or ocean. Activities and land use within the watershed may have an effect on the quantity and quality of water leaving the watershed, whereas activities and land use outside of the watershed will not. Thus, the watershed provides a natural boundary for resource management within.

In the simplest of terms, **integrated water resources management (IWRM)** is the process of managing human activities (including land use) and natural resources on a watershed basis (Figure 1.8). This process takes into consideration the needs of the local environment and ecological species, shown in the red circle. It also includes societal needs, shown in the light brown circle, including consideration of both water quality and quantity. At the same time, proper management allows for both short-term and long-term economic benefits (blue circle), as long as these are sustainable and not damaging to the other two sectors. One can immediately see that a larger, more diverse watershed is sure to result in the need for a more complex IWRM scheme, as it will include many more stakeholders, users, and types of water demands.

The growth of urban areas is the most consistent global phenomenon in our lifetime and will be for some time yet to come. Impervious cover is increased by the proliferation of buildings, roads and highways, parking lots, and housing. Rain can no longer infiltrate into the soil but is forced to run off at a much faster rate with a higher peak flow. Not only is the quantity of runoff altered, but also the quality of the runoff, as the stormwater now contains oils, greases, metals, bacteria, and other suspended solids and particulates. IWRM has become a vehicle for responding to such a phenomenon.

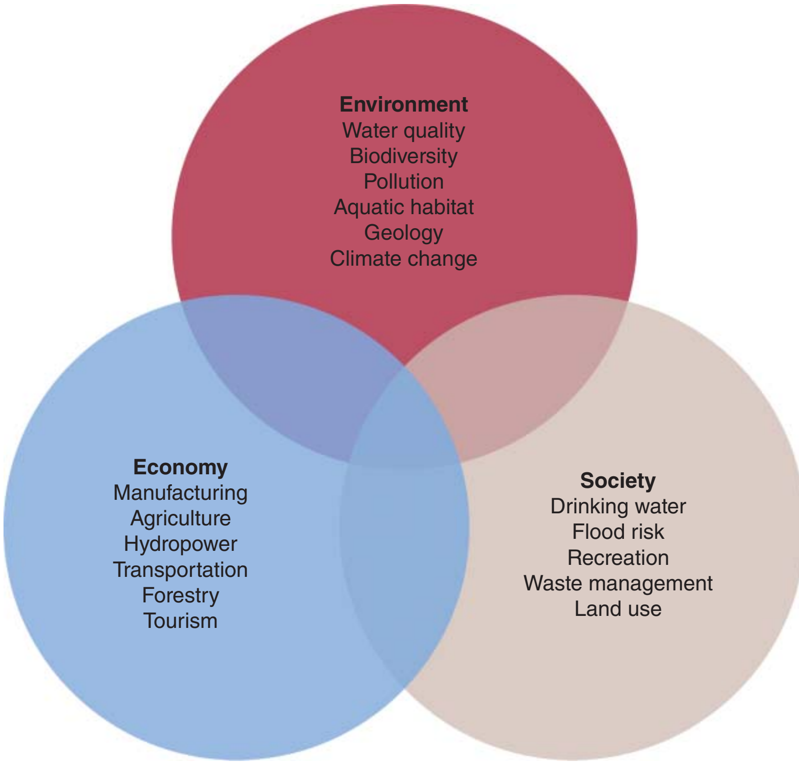

Figure 1.8 Integrated water resources management (IWRM) considers all aspects of environment, society, and economy on a watershed basis. Source: JFC author original.

Ideally, IWRM is a process of decision-making that results in a plan (or strategy) that:

- Is designed to meet both long- and/or short-term targets of water quality, quantity, or equity;
- Contains explicit management options for addressing the stated problem(s);
- Is developed with the support of relevant stakeholders; and
- Has broad public acceptance.

The IWRM process may take many months or years with several iterations in order to come to an agreed-upon conclusion. Even when a true consensus is not reached, the process has both increased awareness of the real or potential threats to water security and has built the community's capacity for decision-making (Heathcote 2009). This process will be described in more detail in a subsequent chapter.

1.7 Levels of Study – Local to Global

The intersection of water supply and demand can happen at different geographic scales. A river can receive its water from within the surface boundaries of its **watershed** (basin) and its subsurface flow, which might extend far beyond that basin. Both the basin and the subsurface flow can cross international (or other jurisdictional) borders. For example, the Rio Tijuana (Tijuana River) is a 120-mile intermittent river that drains in a northwesterly course through northern Mexico and into the US state of California (Figure 1.9). Its waters flow through a salt marsh and a national estuarine reserve before reaching the Pacific Ocean. The marsh is home to hundreds of species of birds and is the largest coastal wetland in California. Beach and ocean health are crucial to the recreation economy just south of San Diego. However, periodic flooding from winter rains frequently overwhelms a small wastewater treatment plant and carries untreated sewage into the marshlands. Sustainable management of this international river system depends upon cooperation of stakeholders speaking different languages on both sides of the border. But the resulting decisions have an impact on many levels – ecosystem services of the marsh, diversity of wetlands species and coastal birds, and socioeconomic benefits of tourism to the local human community (Tijuana River NERR 2010).

A second example is more global in nature. The rising global population is becoming both more urbanized and more middle-class. With this rise comes an increased demand for a more "Westernized" diet, rich in animal-based protein, high-fat dairy products, and high-fructose corn syrup. The water footprint (discussed in a later chapter) of such a diet is substantially higher than a grain-based diet and results in a greater burden upon water resources for agriculture (Black 2016). The ramifications of this dilemma entail local solutions but global implications in the trade of water that is embedded within food products that are traded and transported across the globe.

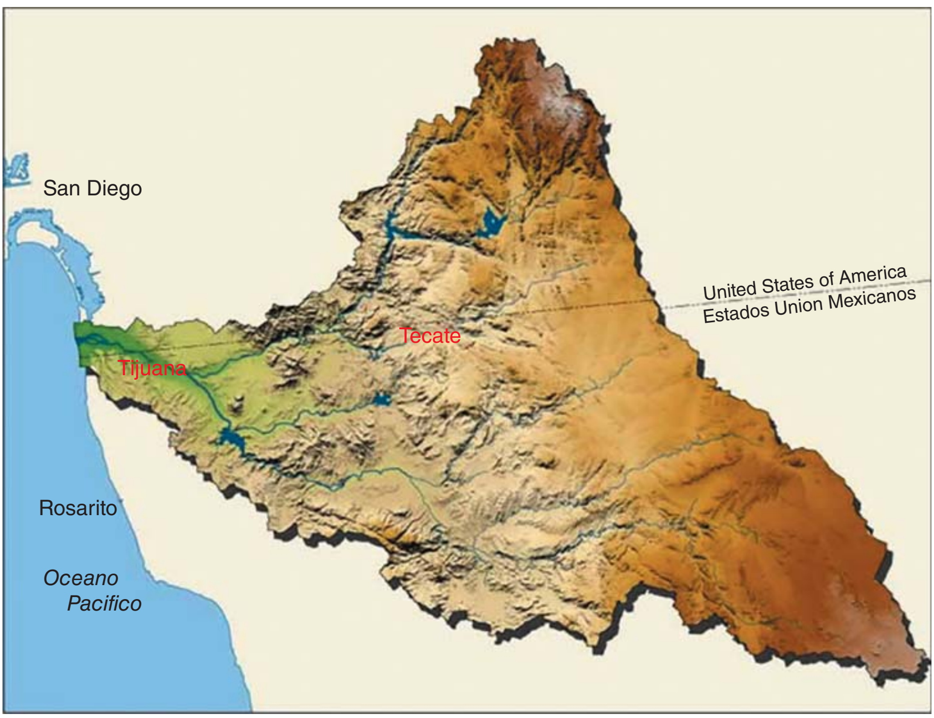

Figure 1.9 The Tijuana River collects water in an arid watershed that straddles two international jurisdictions (Wright and Vela 2005). Source: With permission from San Diego State University Press.

Both examples of water insecurity are complicated by climate change in which drier areas become drier and wetter areas become wetter. The threats to local ecosystems and local agriculture are exacerbated in a warmer global climate, especially when resources for adaptation are limited. This book will address these and many more challenges that face water security.

1.8 Conclusion

In two very ancient texts, water's potential and peril are featured as a subplot to the main narrative. The Yahwist account of creation in Genesis says that "a river rises in Eden to water the garden. Beyond there it divides and becomes four branches." (Gen. 2:10-14). These four rivers are named as the Pishon, Gihon, Tigris, and Euphrates rivers, ancient names for important rivers of modern-day Iraq. These four tributaries flow out to all the known peoples of the time, watering their own gardens and providing the basis for life and culture.

Written even earlier, probably in the 1300s BCE, the first great epic of literature was the story of Gilgamesh, the priest-king of Uruk. In this epic, the city of Shurrupak along the Euphrates river is growing quickly and too noisy for the impatient god, Enlil. He and his fellow gods agree to wipe out all the mortals with a great flood. "The flood and wind lasted six days and six nights, flattening the land. On the seventh day, the storm was pounding like a woman in labor." (*Epic*, Tablet XI). The story was very likely based on a storm of immense magnitude.

Thus, early in our history, water featured prominently in the Fertile Crescent, both in its life-giving richness and in its death-dealing power. Water security, then, has long been integral to the narrative of human flourishing, an anonymous current that becomes part of the rationale for human settlements, movements, and conquests. This volume will help us explore both the qualitative and quantitative aspects of water security, with a focus on the water quantity–quality–equity nexus and with an ample supply of global applications and implications for water management. All these are addressed within the broader context of climate change. In the next chapter, we will survey some important incidents in history in which this narrative was disrupted resulting in human suffering or death, all because of a loss or lack of water security.

*Foundations: Units of Measurement in Water Security

Having thus delved into the world of water security, with its many facets and subcomponents, we end this chapter, as we do most chapters, with a section entitled "Foundations." The purpose of this section is to provide quantitative tools that will be useful in the practice of water security.

Water *quantity* is usually expressed in terms of volume and flow (volume/time) using volume units of gallons, liters, or cubic meters. In hydrology, one also encounters units that describe rainfall volume over a watershed area, such as acre-feet (ac-ft) or hectare-millimeters (ha-mm). Volume units are used for water that is stationary, in lakes, ponds, reservoirs, and tanks, for example. Flow units describe water that is moving in streams, channels, pipelines, and ditches. Groundwater is sometimes described in both volume units to express storage and flow units to reflect its movement. Table 1.3 gives some simple factors for conversion between units.

Water *quality* is often described in terms of concentrations of dissolved substances, expressed in units of mass/volume or mass/mass. These substances may be beneficial to life, such as dissolved oxygen, or harmful at high levels, such as arsenic or hexavalent chromium. The concentration of substances is important as it drives not only toxicity but also the fate and transport of chemicals within the water and between environmental media, such as air and water, or soil and water.

Concentrations are most often expressed in mg/l, understood as the "mass of the substance" divided by the "volume of solution." Since we are working mostly with dilute environmental solutions, the denominator is almost always assumed to be water with a density of ~1000 g/l. To express a concentration unit as mass/mass, we most often use parts per million (ppm_m) or parts per billion (ppb_m). Thus, a concentration of calcium in water may be expressed in two ways:

$$\frac{\text{25 mg of calcium}}{\text{liter of water}} = 25\,{}^{\text{mg}}\!/_{\text{l}} \times \frac{1\text{ l}}{1000\text{ g}} \times \frac{1\text{ g}}{1000\text{ mg}} = \frac{25}{10^6} = 25\text{ ppm}_\text{m}$$

Table 1.3 Commonly used units for area, volume, and flow of water.

Unit A	Multiply A by ____ to obtain B:	Unit B
AREA		
acre	43 560	square feet
hectare	10 000	square meters
hectare	2.47	acres
VOLUME		
gallons	3.8	liters
cubic meters	1000	liters
cubic meters	35.3	cubic feet
cubic feet	28.3	liters
acre-in	10.3	hectare-mm
acre-ft	325 851	gallons
FLOW		
gpm	3.8	lpm
cfs	1700	lpm
cms	35.3	cfs
MGD	3785	m^3/day

When the gram molecular weight of a substance is known, this concentration can also be expressed in *molarity*, or moles/liter:

$$\frac{25\text{ mg of calcium}}{\text{liter of water}} = 25\,^{\text{mg}}\!/_{\text{l}} \times \frac{1\text{ mole Ca}}{40\text{ g Ca}} \times \frac{1\text{ g}}{1000\text{ mg}} = 0.00625\text{ moles Ca/l}$$

Sometimes, it is important for us to know the concentration of a *common constituent* in several compounds. For example, nitrogen may be present in the form of nitrate (NO_3^-), ammonia (NH_3), or ammonium (NH_4^+). We can use simple stoichiometry (ratio of chemical components) and the molecular weights to determine the concentration of the constituent of concern. Consider a water sample with two nitrogen species – 30 mg/l of ammonia and 5 mg/l of nitrate (Mihelcic and Zimmerman 2014). We want to know the partial contribution of N to each species and for the total solution:

$$\frac{30\text{ mg NH}_3}{\text{liter}} \times \frac{\text{mole NH}_3}{17\text{ grams}} \times \frac{1\text{ mole N}}{1\text{ mole NH}_3} \times \frac{14\text{ g}}{\text{mole N}} = \frac{24.7\text{ mg NH}_3 - \text{N}}{\text{liter}}$$

$$\frac{5\text{ mg NO}_3^-}{\text{liter}} \times \frac{\text{mole NO}_3^-}{62\text{ g}} \times \frac{1\text{ mole N}}{1\text{ mole NO}_3^-} \times \frac{14\text{ g}}{\text{mole N}} = \frac{1.1\text{ mg NO}_3^- - \text{N}}{\text{liter}}$$

The total contribution of nitrogen (N) to this solution is $24.7 + 1.1 = 25.8$ mg/l.

Another aspect that illustrates the importance of nitrogen units is the drinking water standard for nitrate. We may see this standard listed as 10 mg/l in one place but 45 mg/l in another place. This seeming inconsistency can be rectified by realizing that 45 mg/l as nitrate is the same as 10 mg/l of nitrate *as nitrogen*:

$$\frac{45\text{ mg NO}_3^-}{\text{liter}} \times \frac{\text{mole NO}_3^-}{62\text{ g}} \times \frac{1\text{ mole N}}{1\text{ mole NO}_3^-} \times \frac{14\text{ g}}{\text{mole N}} = \frac{10\text{ mg NO}_3^- - \text{N}}{\text{liter}}$$

Thus, when a value of nitrate is reported, it is important to know if it is reported as nitrate (NO_3) or as nitrate-nitrogen (NO_3-N) so we know whether to compare it to 10 mg/l or 45 mg/l as the standard. For example, 30 mg/l of nitrate exceeds the standard if it is 30 mg/l of NO_3-N but is below the standard if it is 30 mg/l of NO_3.

We do well to use different units in different situations. It is human nature that we are more comfortable working with numbers in a certain range of magnitude. For example, we sometimes express salinity in ppt (thousands) or ppm. Seawater, for example, has a salinity of 35 ppt or 35 000 ppm. We would not use ppb for seawater as this would be noted as 35 000 000 ppb. Conversely, we would use ppb for the arsenic standard (10 ppb) versus ppm (0.01 ppm) or ppt (0.00001 ppt). We have a preference to work with numbers closer to one versus numbers much greater or less than one and pick our units accordingly. Likewise, the unit of ac-ft is convenient for the volume of a lake (e.g. Lake Thunderbird in Norman, OK, has an average volume of 120 000 ac-ft) as that is a more manageable number than gallons (3.9×10^9 gal). So, while some units may seem strange to us (ppt or acre-ft), they allow us to express numbers in an order of magnitude that is more comfortable to us.

As we proceed through our study of water security, we will see many examples of water volumes and chemical concentrations in water. A potentially harmful chemical, such as arsenic or chromium VI, may not be easily seen (Figure 1.10), but it is always important from the perspective of water safety and security.

Figure 1.10 Chemical concentrations in a dilute solution of tap water may not always be visible, but they are important for water security. Source: New Africa/Adobe Stock.

End-of-Chapter Questions/Problems

1.1 Compare and contrast the two definitions of water security given by the GWP and the United Nations on the basis of scope, incorporation of threats, and goals/outcomes.

1.2 Use an Internet search (e.g. the FAO-Aquastat database) to answer the following questions for the country of Angola (latest data available):
a. What is the total surface water produced internally? (m^3/year)
b. What is the total groundwater produced internally? (m^3/year)
c. What is the overlap between surface water and groundwater? (m^3/year)
d. What is meant by the "overlap"?
e. How is the total IRWR (internal renewable water resources) calculated? Give equation in word form.

1.3 Use the FAO-Aquastat database to compare the percentages of freshwater withdrawals between Australia and the United Kingdom.
a. What is percent (%) withdrawals for agricultural, municipal, and industrial sectors in Australia?
b. What is percent (%) withdrawals for agricultural, municipal, and industrial sectors in the United Kingdom?
c. Comment on the differences between these two nations.

1.4 Using the latest census figures and the FAO-Aquastat database, calculate the water-stress level (m^3/cap-year) for the following nations:
a. Vietnam
b. Iraq
c. Peru
d. Spain
e. Comment on the differences (or similarities) between these nations.

   f. Why is this indicator perhaps a poor water-stress indicator for large nations such as Peru and Spain?

1.5 Groundwater is a very valuable stored resource as it usually does not undergo evaporation and remains in place until tapped by the human community. How much of the internal renewable water resources is groundwater (%) in each of the following nations?
   a. Chile
   b. Haiti
   c. Canada
   d. Venezuela
   e. Belgium
   f. How might this single metric be a good indicator of water security? What are the constraints upon accessibility for this stored resource?

1.6 The Chesapeake Bay watershed is an important, large, and complex watershed. Use the Internet to retrieve a management plan for some portion or all of this watershed and describe at least three specific management strategies that are recommended to protect the watershed.

1.7 Find a watershed-protection plan for a watershed near where you live.
   a. What are the major challenges in this watershed?
   b. What are the specific management strategies that are being recommended?

1.8 Conduct an Internet search for information on the Tijuana River Watershed. How does social equity play a role in the management of this watershed?

1.9 A 2-l water sample was analyzed and found to contain 40 mg of sulfur, whose molecular weight is 32 g/mole.
   a. What is the concentration of sulfur in mg/l?
   b. What is the concentration of sulfur in ppm_m?
   c. What is the concentration of sulfur in moles/l?

1.10 Three different water samples were analyzed and found to contain the following concentrations of nitrate and nitrite. Convert these concentrations to nitrate-N and nitrite-N basis, sum them, and see if the samples exceed the combined nitrate+nitrite standard of 10 mg/l as nitrogen.
   a. 10 mg/l of nitrate/30 mg/l of nitrite
   b. 20 mg/l of nitrate/20 mg/l of nitrite
   c. 30 mg/l of nitrate/10 mg/l of nitrite

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2

Historical Examples of Water Insecurity

In this chapter, readers are introduced to past examples of the lack of water security, delineated by a lack of sufficient quantity of water of acceptable quality to meet the needs of all members of society. These instances of water insecurity sometimes resulted in widespread social disruption, morbidity, and death. In many cases, the affected populations responded with technological solutions, such as the aqueducts from ancient Rome or provisional wastewater reuse in modern-day Texas. In some cases, the insecurity led to the creation of new public health practices or institutions, such as in the cases of London and Chicago. The global proliferation of dams has led to conflict over who reaps the benefits, and who pays the costs, for such major hydrologic alterations. While emerging economies are especially vulnerable to water insecurity, developed nations are also vulnerable, although they have many more resources with which to respond.

Learning Objectives

Upon completion of this chapter, the student will be able to:

1. Describe several historical instances in which there was insufficient quantity of water, such as periods of drought, and the resulting social effects.
2. Describe several historical instances in which there was water of dangerous quality, such as contaminated with biological pathogens, and the social effects of the degraded water.
3. Describe historical instances in which one segment of society was excluded from water of sufficient quantity and quality, producing inequities of human development.
4. Describe a modern instance in which climate change is a significant factor in water insecurity.
5. *Understand the basic concepts of mass balance and reaction kinetics as it relates to population growth and contaminant reduction.

2.1 Introduction

In the ancient world civilizations needed water for survival, causing new settlements to locate near a dependable water source, such as a spring or river. But they also formed population clusters based on additional factors, such as topography, economy, and security.

Fundamentals of Water Security: Quantity, Quality, and Equity in a Changing Climate, First Edition.
Jim F. Chamberlain and David A. Sabatini.

Companion website: www.wiley.com/go/chamberlain/fundamentalsofwatersecurity