Contents

1 Introduction

This chapter sets the stage for the rest of the book by introducing some major themes:

- Water plays a central role in both ecosystems and society. All the most important environmental issues of our day—from climate change to the biodiversity crisis, from environmental justice to global development—have a strong water component.
- We are experiencing a multifaceted water crisis with serious impacts on human and ecological health; this crisis is playing out in location-specific ways but also has global aspects.
- The water crisis demands increased attention to justice and sustainability in water management.
- Better water management will require a mix of locally appropriate green and gray infrastructure, as well as increased attention to institutions, incentives, and information.

We start the chapter by placing the water crisis in the broader context of ongoing societal changes, sometimes called the Great Acceleration. We then turn to describing the central role that water plays in society and the way that the water "hard path" has contributed to the Great Acceleration. A brief summary of the global water crisis provides the pivot point of the chapter, leading us to a discussion of water ethics and tools for improved water management.

1. The Great Acceleration and the Just Transition

We are at a critical juncture in the history of humanity and of the planet we inhabit. The human footprint on Earth has grown so rapidly over the last few generations that we are now endangering the planetary systems that have allowed us to thrive. The decisions we make now will affect Earth and all its inhabitants for many millennia.

Let's take a moment to reflect on how we got here.

Many of us take for granted the basic parameters of life in a developed economy in the twenty-first century. Our lives are built around certain assumptions: that our homes will have running water and flush toilets, that antibiotics and surgical care are available when we need them, that we can pursue careers that don't necessarily involve growing food, and that we can quickly communicate and travel across great distances.

All these features of our lives were (to a greater or lesser extent) unavailable to people anywhere in the world a mere 200 years ago. And some of them are still unavailable today to many people around the world, including in the United States.

To provide a bit of historical perspective, Figure 1-1 shows some indicators of how human society has changed over the last 10,000 years. The most notable feature of these graphs is the ***Great Acceleration*** that began with the Industrial Revolution and continues to this day: the exponential growth in human population and impact on the natural world. We have truly entered the ***Anthropocene***: the geologic epoch characterized by the dominance of humanity as the primary force shaping the state of our planet.

With these graphs in mind, allow me to sketch four alternative narratives about where we have come from and where we stand now.

The first narrative celebrates our accomplishments as humans. Beginning with the invention of agriculture, continuing with the development of writing and complex civilizations, and culminating with the Industrial Revolution and the Digital Revolution, our story is one of increasing control over our own fate. Our lives are longer than ever before and are filled with possessions and technologies that previous generations couldn't dream of. We have figured out how to grow food so efficiently that most of us can specialize in a variety of other activities; this specialization has allowed us to improve our standard of living, create beautiful works of art, and explore the frontiers of science. Most fundamentally, our success as a species is told by our increasing numbers—a result of greater food production, improved health care, and lower mortality. This is the story told by the technological optimist, who believes human ingenuity will continue to increase our productivity and solve any problems that emerge.

The second narrative focuses on the uneven distribution of the benefits and costs of our technological age. This story brings to the fore the billions of people who lack access to adequate water, food, and other basic services, even as others spend extravagantly on luxuries. It reminds us that our consumer lifestyles depend on exploitation of people half a world away (or in our own neighborhoods), through invisible networks of mining, environmental degradation, dispossession, forced labor, and toxic waste. It highlights the central role of colonialism in creating and maintaining global inequalities. It questions whether emerging technologies will be used to level the playing field or to bring more power to the powerful. It demands that all our decisions take into account the needs and rights of the most vulnerable.

The third narrative sees an existential threat to humanity itself in our increasing numbers and our global impact. This story recognizes that a finite planet cannot sustain indefinite growth and that our boom must inevitably be followed by a bust—unless we can quickly stabilize, and then reduce, our population and our consumption rates. In this narrative, the unrelenting growth of the human footprint on the planet has endangered our own survival by undermining the life support systems of the planet, as exemplified by climate change, pollution, and habitat loss.

The fourth narrative has a longer time frame and a larger lens. In this story, we try to see the perspectives of plants, animals, and ecosystems. We acknowledge the long

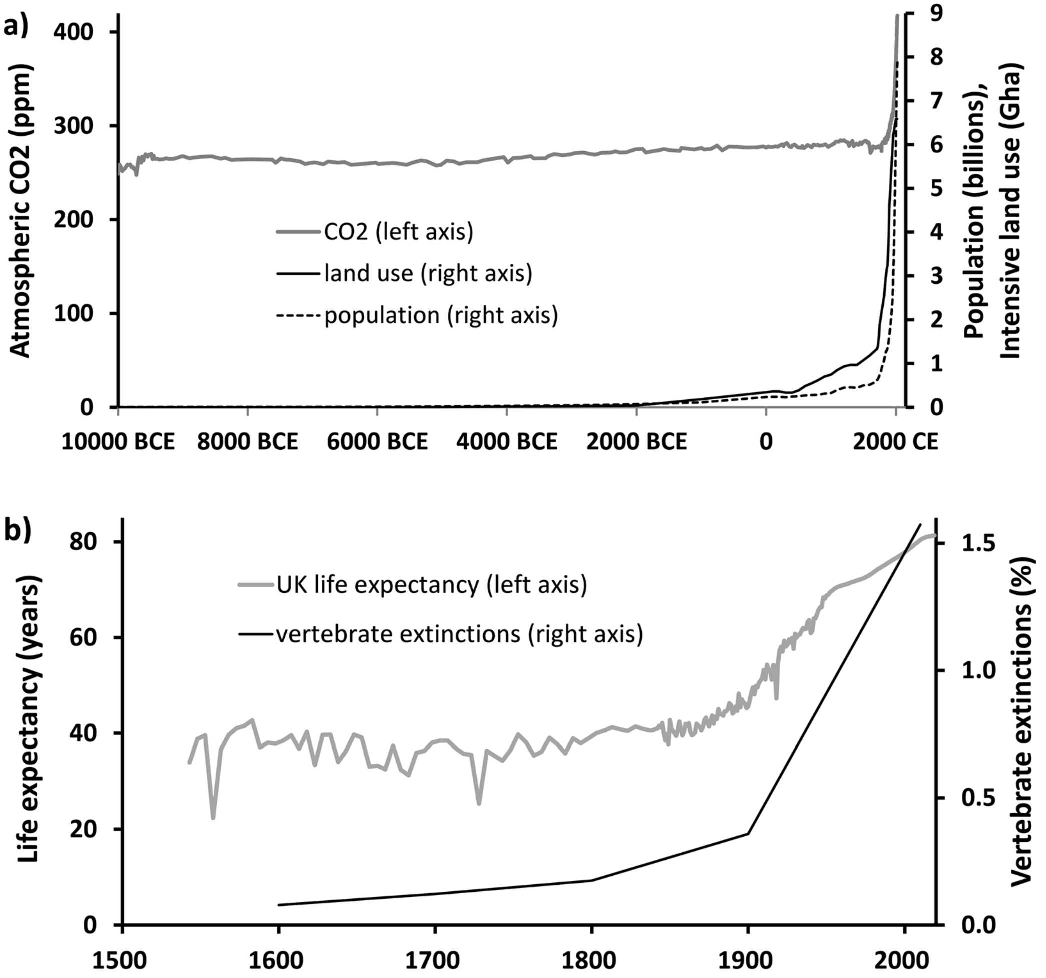

Figure 1-1. Some indicators of change during the Great Acceleration. (a) Atmospheric concentration of carbon dioxide (CO_2), the primary driver of climate change (https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions), area of land in intensive human land use (Ellis et al. 2020), and global human population (https://ourworldindata.org/grapher/population). (b) Life expectancy in the United Kingdom, where good records go back to the sixteenth century (https://ourworldindata.org/life-expectancy), and the percentage of known vertebrate species that have gone extinct (Ceballos et al. 2015; conservative estimate).

history of the globe before *Homo sapiens* first stepped on the scene around 300,000 years ago. We bring to mind the two million species currently known to science, along with the many millions more not yet identified. We recognize that the unprecedented "success" of humanity has come at the expense of other species and at the expense of the planet's complexity, resilience, and beauty. We see ourselves, perhaps, as having forgotten our role as "the younger siblings of Creation,"[1] with much to learn from other species and with reciprocal relations of dependence and responsibility.

The approach I take in this book draws from all four narratives. I believe that humanity's manipulation of the water cycle has brought us many good things (narrative A) but has also contributed significantly to oppression and inequity (B). And

I believe that water management needs to start working *with* nature rather than *against* it—both for our own survival (C) and for the sake of our fellow travelers on this planet (D).

Or, to put it slightly differently, I believe that the central challenge of our age—in water management and beyond—is to bring sustainability and justice into our relationships with the natural world and each other.

Sustainability: We desperately need to reexamine and reclaim our relationship to the natural world and start living in ways that better respect the planet. We need to do what no other species has done: purposely limit ourselves to avoid exceeding the carrying capacity of the planet.

Justice: As we transition to sustainability, we also urgently need to address the power imbalances at the heart of our society. We need to learn how to share nature's bounty fairly, to ensure that everyone has enough, instead of continuing to enrich the powerful. In short, we need a Just Transition.

The issues of sustainability and justice go beyond water, of course. But water has been a central player in the Great Acceleration, and it must be equally central to the Just Transition.

2. The Centrality of Water

Why water? What makes water such an important part of both the Great Acceleration and the Just Transition? This section summarizes the underlying characteristics of water that make its impact on human society so far-reaching.

2.1. Water and the Human Spirit

Water plays a dual role in our lives. On one hand, it is a commonplace, as close as our bodies and as familiar as our kitchens. But it is also the animating force of the planet, the power of nature manifest in thunderstorms, mighty rivers, the vast ocean. In nature, water tends to inspire awe, ecstasy, contemplation. In our homes, water tends to evoke indifference—except when the taps go dry and we become suddenly, humbly aware of our supreme dependence on the thin thread that connects nature's water to ours.

Water is considered sacred in many religious traditions. Water is often viewed as the source of all life, and its ritual use tends to symbolize rebirth, cleansing, and purity. Many religions treat specific water bodies as particularly holy: the Lourdes Spring in Catholicism, the Zamzam Well in Islam, the Ganges River in Hinduism. In indigenous traditions, water is often seen as "an autonomous and primeval element to be encountered with humility, respect, joy and caution."[2]

2.2. Water as a Human Right

Water is, of course, indispensable for all living things on Earth. For people, water is a daily necessity, not just for drinking but also for preparing food and for cleaning ourselves. In addition, access to adequate sanitation is necessary for protecting human health, since inadequate disposal of human wastes leads to water contamination and disease transmission.

In 2010, the United Nations acknowledged these basic needs by passing resolution 64/292, which recognized "safe and clean drinking water and sanitation as a human right that is essential for the full enjoyment of life and all human rights." Still, millions of people around the world (including in the United States) struggle to access sufficient safe water and adequate sanitation solutions, and 1.5 million people die annually from preventable water-related diseases.

2.3. Water Use

Water is used in all aspects of our society and economy: growing food, generating power, making consumer products, transporting goods. Almost any daily activity you can think of has some water requirement, whether obvious or hidden.

In thinking about how we use water, we should note that water can take different forms, with differing availability for human use. Most obviously, water can be found as a solid (ice), liquid, and gas (water vapor); while human water use relies mostly on liquid water, the solid and gaseous forms are also of interest to water managers, whether as storage (seasonal snowpack) or as a potential new supply (water vapor capture). Less obvious but equally important is the distinction between ***blue water***—water in the simple liquid or solid state—and ***green water***: water in the soil that is adsorbed to soil particles. Green water can't be moved around and used to meet human water demand, so water management focuses primarily on blue water, but green water can be used by plants as a water source, so it is critical for supporting vegetation, including rainfed agriculture (in contrast to irrigated agriculture, which involves adding blue water to fields).

Uses of blue water can be grouped into two categories, which provide much of the structure for this book: ***offstream*** uses, where water is withdrawn from rivers or other water sources for use in households, farms, industry, or power plants; and ***instream*** uses, where water provides benefits to humans without being removed from the environment, as when we use a river for navigation, power generation, fishing, or recreation. These different uses are often competing for a limited supply of water, potentially leading to conflict at scales ranging from an individual irrigation ditch to international basins.

Many of the ways we use water—even when they involve offstream use—don't actually *use up* that water. The concept of ***nonconsumptive*** water use will be covered in more detail in Chapter 4, but for now just imagine the water you use to flush the toilet; it goes down the pipes, but then where does it go? Unless you live in a rural area or right along the coast, it probably goes to a wastewater treatment plant and then back into a river, where it is subsequently reused by another community downstream. This illustrates two fundamental facts about water: It can be reused multiple times, and upstream users may contaminate the water needed by downstream users.

2.4. Water as a Resource

The ubiquity of water in our lives means that water is a vital economic resource for individuals, companies, cities, and countries. As an economic resource, water has several unique characteristics that affect how it is managed.

- Water is both visible and invisible. Globally, most of the water we use is visible surface water drawn from lakes, rivers, or reservoirs. But a significant (and increasing) fraction of our water use comes from belowground water resources—ground-

water—found in formations known as ***aquifers***. Groundwater poses a serious management challenge because it is widely distributed, hard to monitor, and susceptible to overuse.
- Unlike oil or coal, water is a ***renewable resource***. The hydrologic cycle constantly replenishes the supply of water in rivers, and each year's supply is independent of whether last year's supply was used up.[3] On the other hand, there are also nonrenewable (or slowly renewable) stores of water, such as lakes and aquifers; when we use those stores more rapidly than they are replenished, the stock of water is depleted, so this water use is ultimately unsustainable.
- Unlike oil or coal, water is not substitutable in many of its most important uses. If we run out of oil, we can find other ways to generate energy. But there is no substitute for water for drinking, growing food, or providing habitat. At the same time, some uses of water *are* substitutable—we could use composting toilets instead of flushing with water, we could clean our sidewalks with a broom instead of a hose—so in times of scarcity, water should be reserved for the most essential uses.
- Water is considered a ***fugitive resource***, meaning that it moves on its own and can't be completely constrained by any one owner. For example, if I install a well on my property and pump water from a shared aquifer, groundwater will move from under my neighbor's property to my well. Rules for water allocation must acknowledge this physical fact about water and figure out how to deal fairly with these types of situations.
- Water availability (supply) is highly variable in both space and time. Some regions have lots of water, some have much less, and many face both droughts and floods. This variability has always been one of the central challenges facing water managers, but climate change and land-use change are increasing this variability.
- Water supply and demand are hard to monitor, and since "you can't manage what you don't measure," this makes water hard to manage. On the supply side, the difficulty stems from water's high variability, multiple forms and locations, and variable quality. On the demand side, some of the most important uses are inherently

Box 1-1. Local and Global Water Problems

The local versus global nature of water problems is an important theme that we will return to throughout the book. On one hand, water—unlike oil—is not a globally traded commodity, so each watershed must deal with its own scarcity, flooding, and pollution problems, thus giving water problems a fundamentally local character. On the other hand, as we will see, there are several aspects of water issues that do operate at larger scales:

- Complex atmospheric ***teleconnections*** mean that water consumption and land use in one region can affect water availability in other regions.
- Climate change is a global issue (since greenhouse gas emissions anywhere affect climate everywhere) with significant impacts on water availability around the world.
- Global trade in agricultural and industrial products results in global movement of ***virtual water***: the water that it took to make those products.
- Certain pollutants are transported around the world and thus are regulated by international treaties.

difficult to measure (e.g., groundwater irrigation), but we have also done a poor job investing in monitoring systems.

- Water is heavy, or, as an economist would put it, water trades have high ***transaction costs***. What this means is simply that significant energy is needed to move water from one place to another—especially uphill—in amounts that are large enough to matter. One implication of this is that—unlike oil, which is profitably transported around the world—water supply networks tend to be local and constrained by topography. Thus, water problems tend to be local, though with some important exceptions (Box 1-1).
- Despite being essential to life, water is generally cheap. Eighteenth-century economist Adam Smith wondered about this in his famous diamond–water paradox: Water is clearly more useful than diamonds, so why is it so much cheaper? The short answer is that water is much more abundant than diamonds, so the ***marginal benefit*** of an additional increment of water is low. Box 1-2 explores these ideas in more detail.

2.5. Water and Global Development

Given its strong links to both human health and economic development, water is featured prominently in the agendas of the World Bank, the World Health Organization (WHO), and other global development agencies. These agencies generally work on water issues within the framework of ***sustainable development***, a concept that, broadly speaking, means improving people's lives, especially in low-income countries (*development*), without destroying the ecological life-support systems needed by future generations (*sustainability*).

In order for ***low- and middle-income countries*** (LMICs) to achieve growth and lift their citizens from poverty, they must develop their water resources (although whether they need to do so following the same path as high-income countries is a question that we will wrestle with in later chapters). As two development economists put it in an influential 2007 article, "For those countries that have not achieved water security, this objective lies at the heart of their struggle for sustainable development, growth and poverty reduction."[4] They go on to define water security as "the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economies." This definition draws our attention to both the positive (the use of water to support our health, economies, and ecosystems) and the negative (the potential of water-related hazards, such as droughts and floods, to damage those same values).

Over the last several decades, international goals for sustainable development have included specific targets for water management. The ***Millennium Development Goals (MDGs)*** were a series of eight goals, meant to set the international development agenda for 2000–2015, ranging from "eradicate extreme poverty and hunger" to "develop a global partnership for development." These goals were translated into twenty-two targets, but water issues appeared in only one of these targets.

For the post-2015 period, the MDGs were replaced by ***the Sustainable Development Goals (SDGs)***, a more ambitious set of seventeen goals and 169 targets. Water issues are treated much more broadly in the SDGs, with Goal 6 ("ensure availability

Box 1-2. Marginal Benefits and the Diamond–Water Paradox

The solution to the diamond–water paradox lies in the concept of marginal benefits, coupled with the higher abundance of water relative to diamonds. If we think about the benefit provided to an individual by different levels of water use, it might look something like Figure 1-B1. The benefit of a small, initial increment of water is high (the curve rises quickly), but as more water is available, the water is being used for uses that are increasingly less valuable, and the benefit curve levels off. Thus, the marginal benefit—the benefit provided by an additional increment of water (i.e., the slope of the curve shown in Figure 1-B1)—decreases as more water is available (Figure 1-B2).

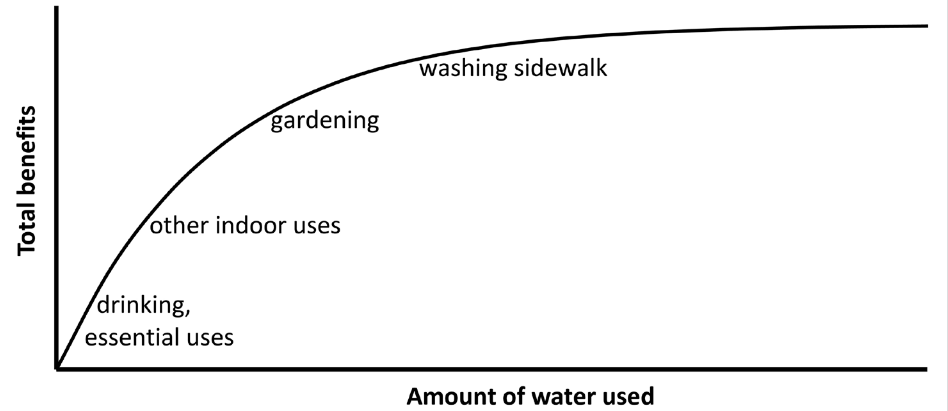

Figure 1-B1. Benefits provided by water use. As more water is available, it is put to increasingly less valuable uses. (Uses shown are illustrative only.)

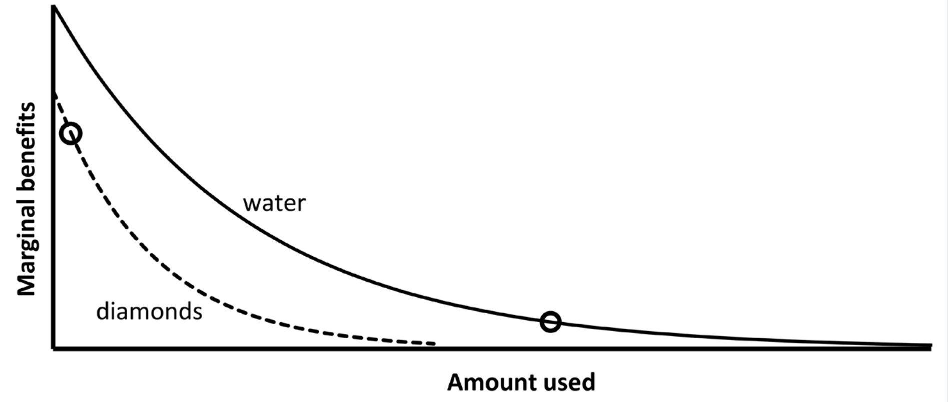

Figure 1-B2. Marginal benefits provided by water and diamond use. The curve shown for water corresponds to the slope of the curve in Figure 1-B1. Circles indicate typical amounts of water and diamonds.

Diamonds, too, have a declining marginal benefit curve, but since diamonds are much less abundant than water, our position on the diamond curve (indicated by the circle in Figure 1-B2) is much higher than our position on the water curve. In other words, given that water is often abundant—and diamonds are not—the marginal benefit of the next increment of water is lower than that of the next diamond. And it is the marginal benefit that determines the price. In fact, the marginal benefit curve is also known as the demand curve, since it expresses how much a person would be willing to pay for a given amount of the product.

Table 1-1. Summary of targets and indicators under Goal 6 of the SDGs. Several of these are discussed in this book; the remainder are covered on the companion website.

Target	*Indicator*
6.1. Drinking water	6.1.1. Drinking water access
6.2. Sanitation	6.2.1. Sanitation access
6.3. Water quality	6.3.1. Wastewater treatment
	6.3.2. Ambient water quality
6.4. Water scarcity	6.4.1. Water-use efficiency
	6.4.2. Water stress
6.5. Integrated water resource management (IWRM)	6.5.1. IWRM implementation
	6.5.2. Transboundary cooperation
6.6. Aquatic ecosystems	6.6.1. Aquatic ecosystems
6.a. International funding	6.a.1. International funding
6.b. Local participation	6.b.1. Local participation

and sustainable management of water and sanitation for all") being broken into eight targets and eleven indicators (Table 1-1).[5]

2.6. *The Water–Energy Nexus*

Energy, like water, is used in every part of our society, and there are close linkages between energy and water in both natural cycling and human use. There has been increasing interest in understanding and managing the linkages between the two sectors, a task that is made more difficult by the traditional siloing of energy and water into different academic fields and management agencies. Throughout the book, we will explore several of the linkages that make up the ***water–energy nexus***:

- Climate change, driven primarily by our use of ***fossil fuels*** for energy, is changing the spatial and temporal patterns of water availability (Chapter 3).
- The availability of cheap energy is one of the underlying drivers of modern water management (Chapter 4).
- The search for "clean energy" is driving massive hydroelectric dam projects (Chapter 6).
- Water–energy exchanges are potential tools for transboundary cooperative management (Chapter 12).
- Water and wastewater treatment use significant amounts of energy. Some newer technologies for water supply, such as desalination, wastewater reuse, and water vapor capture, are quite energy intensive (Chapter 13).
- Energy systems require large amounts of water and can also be significant sources of water pollution (Chapter 17).

2.7. *Water and Ecosystems*

Freshwater ecosystems—rivers, lakes, and wetlands—are hotspots of biodiversity, serving as home to about 10 percent of all species and 30 percent of all vertebrate species while covering less than 1 percent of the Earth's surface.[6] These ecosystems are particularly vulnerable to habitat degradation and anthropogenic changes in the quantity and quality of freshwater flows. The Living Planet Index—a measure of species abundance around the world—suggests that freshwater organisms are declining rapidly, with a 76 percent decrease in migratory freshwater fish and an 83 percent decrease in freshwater populations more broadly over the period 1970–2018 (compared with a 69 percent decrease for all species measured).[7]

In one of the saddest consequences of water management, anthropogenic impacts on freshwater ecosystems have led to several species extinctions. A recent example is the Chinese paddlefish, a large (up to 7 meters long) migratory fish that survived for tens of millions of years but could not withstand overfishing and damming of the Yangtze River.[8]

In response to this crisis, a group of scientists has called for an Emergency Recovery Plan for Freshwater Biodiversity,[9] focused on addressing the six primary threats to these organisms, which we will cover throughout the book:

- Changes in flow (Chapter 5)
- Water pollution (Chapter 8)
- Habitat degradation (Chapters 6 and 7)
- Overexploitation of fish (Chapter 6) and river sand (Chapter 17)
- Invasive species (Chapter 6)
- Habitat connectivity (Chapters 7 and 9).

Besides their value as habitat, aquatic ecosystems also provide great value to society, as expressed in the concept of ***ecosystem services***, defined as “the benefits that people derive from functioning ecosystems” either directly or indirectly.[10] Ecosystem services are often categorized as provisioning services (e.g., water supply), regulating services (e.g., moderation of extreme events, wastewater treatment), habitat services (e.g., maintenance of genetic diversity), and cultural services (e.g., recreation, mental and spiritual health).[11] Freshwater ecosystems are estimated to have higher ecosystem service values (per unit area) than any other nonmarine biome.[12]

3. The Water Hard Path and the Global Water Crisis

Given that water is indispensable to our health and our economy, it is not surprising that the manipulation of water has played a central part in the Great Acceleration and the creation of the modern age. We will explore that history more fully in Chapter 4, but here we briefly introduce the ***hard path*** that has characterized modern water management.

The last two centuries have seen rapid increases in water use, increases that have improved our health and quality of life in many ways but have also driven widespread water pollution and the devastation of aquatic ecosystems. Water management during this period has been dominated by an approach that has been called the hard path, which can be characterized by its technologies and attitudes:

- Technologies: The hard path relies heavily on ***gray infrastructure***—large-scale, centralized, highly engineered infrastructure requiring high inputs of materials and energy—especially aqueducts, levees, dams, wells, and water treatment plants. These technologies are typically implemented in a uniform manner, regardless of local conditions or community preferences.

- Attitudes: The hard path is grounded in the belief that nature is a set of resources for human exploitation and that the best way to advance human well-being is to dominate and control the natural world. In addition, the hard path is typically technocratic, with little room for the knowledge and values of local communities.

Despite the engineering successes associated with the hard path, we now face a moment of crisis.

The media and many water experts agree that we are facing a global water crisis, but there is less consensus on exactly what the crisis is. In fact, it often seems that there are multiple distinct water crises; this diversity of crises reflects both the multifaceted ways that water touches our lives and the local nature of water systems.

The flooding crisis: Unprecedented rainfall. Rising seas. Swollen rivers. Failing levees. Catastrophic mudslides. Homes and infrastructure destroyed. Survivors plucked from rooftops.

The scarcity crisis: Drought. Crop failures. Household taps running dry. Dropping water tables. Shrinking reservoirs. More straws desperately trying to suck from a dwindling supply.

The access crisis: Billions of people in poor countries (and millions in the US) still lacking safe, accessible water and sanitation. Aging treatment plants and leaky pipes in our cities. Skyrocketing water prices as we foot the bill for repairs.

The health crisis: Children (2,000 a day!) dying from contaminated water. Cholera resurgent. Carcinogens in our drinking water. Lead in our blood. Our beaches making us sick. Our cultural, social, and mental health frayed by lost connections to healthy waterscapes.

The displacement crisis: Millions of people displaced directly by dams, reservoirs, and levees—or indirectly by the ecological impacts of that infrastructure. Farmers migrating to cities as their crops suffer from drought or flooding.

The conflict crisis: Countries fighting over how to share a limited water supply. Insurgents using water as a weapon. Farmers and environmentalists squaring off over endangered fish. Endless litigation over the arcana of water law.

The ecological crisis: Rivers that don't reach the ocean. Dry lakebeds that send up clouds of toxic dust. Species that evolved over millions of years, gone in a generation. "Sacrifice zones" to support our consumptive lifestyles. The loss of food sovereignty for fish-dependent cultures.

Each of these is a genuine crisis. Yet these problems are—at least at the surface—different enough from each other that we are often tempted to focus on one or another as the *true* crisis, with the choice determined mostly by where we are looking and what lens we are looking through. Our challenge in this book is to pay serious attention to each of these crises and to understand how they are linked.

Is there a common thread, then, that unites these crises? Can we look underneath these symptoms of crisis and find deeper causes of crisis—and corresponding solutions?

Broadly speaking, the underlying causes of crisis lie in the stresses of the Great Acceleration and the shortcomings of hard path water management. The remainder of this chapter will explore causes and solutions in more detail, from two perspectives: values (Section 4) and management tools (Section 5).

4. A Water Ethic: Justice and Sustainability

To better understand the global water crisis, it is helpful to back up a step and think about what values we want water management to support. Many water decisions involve ethical choices, and seeing the underlying values more clearly may help us understand the strengths and weaknesses of current water management. In this section, we discuss the dominant ethic of the hard path—utilitarianism—and make the argument for emphasizing justice and sustainability in a modern water ethic.

Imagine a river with multiple demands on it: Farmers want water for irrigation; city residents want water for household use, including watering their lawns; an endangered freshwater mussel needs water in the river to survive. How do we divide up the limited supply? Or imagine a proposed hydroelectric dam project that will provide green energy for a developing country but will also inundate traditional fishing grounds: Should the dam be built? Or: Should we build levees that will protect a community from flooding but destroy wetlands? Competing values are at play in each of these scenarios.

Until recently, the (often implicit) ethic driving such decisions in modern water management was ***utilitarianism***, a philosophy encapsulated in the maxim "the greatest good for the greatest number." Under a utilitarian ethic, the right course of action is that which will maximize overall human utility (often equated to well-being or happiness). While some utilitarian thinkers do include the well-being of sentient animals in their moral calculus, utilitarianism in practice tends to focus on maximizing benefits to humans only. In addition, utilitarianism in practice tends to quantify utility solely in monetary terms, using tools such as ***benefit–cost analysis (BCA)***, which evaluates potential projects based on comparing costs and benefits through the common currency of dollar value.

This focus on quantifiable benefits and costs to humans means that utilitarianism has a bias toward actions that produce large short-term economic benefits, even if the long-term ecological or social costs—which are often hard to quantify—may be equally large. Thus, in the examples above, utilitarianism would generally favor cities and farms over mussels, hydroelectric power over small-scale fishing, and levees over wetlands.

Utilitarianism also tends to focus on aggregate human utility and sidestep the issue of the distribution of benefits across different populations. For example, BCA operates under the concept of *Kaldor–Hicks efficiency*, in which a project is beneficial if the gains to the winners are larger than the costs to the losers. The logic is that if the project produces aggregate gains, those gains could be redistributed so that everyone comes out ahead—but there is no requirement that this redistribution actually take place. This contrasts with the concept of ***Pareto efficiency***, in which a project is beneficial only if no one is made worse off (and there is benefit to at least one person). Since most public policies have negative impacts on some individuals, Pareto efficiency is probably too strict a standard; still, fairness seems to require that people who are giving up something for the public good should be compensated in some way.

In sum, utilitarianism tends to focus on a narrow slice of water's potential values—its ability to drive economic development—and ignore other social and ecological values. To incorporate those other values, we need to draw on concepts of justice and sustainability.

4.1. Justice

So far, we have used the term *justice* broadly to evoke the social values not included in utilitarianism. But we can be a bit more precise about what we mean, by identifying three aspects of justice that should be part of our water ethic:

- Participatory justice: Since water is central to life, water management decisions affect everyone. Communities and individuals thus have a right—even a responsibility—to participate in those decisions. In the past, a specialized water elite has made decisions that affect us all, through opaque and exclusionary processes. A contemporary water ethic must give communities—especially those who have historically been marginalized—a seat at the table.
- Distributive justice: The costs and benefits of water management need to be shared fairly. Ethicists have identified a variety of ways to define a "fair" distribution of goods:
    - Under *strict equality*, every person should receive an equal share of costs and benefits (or at least equal opportunity to access those benefits). Western societies have generally rejected strict equality for various reasons, most notably the desire to create incentives for entrepreneurial wealth generation.
    - Under the *sufficiency principle*, an unequal distribution of benefits is acceptable as long as everyone has "enough" (a term that admittedly can sometimes be hard to define).
    - Under the *difference principle* (proposed by philosopher John Rawls), social and economic inequalities are acceptable as long as they raise the absolute well-being of the least advantaged members of society.

  In this book, we will draw on both the sufficiency principle and the difference principle; that is, we will be thinking about ways to ensure that everyone has access to the basic water services they need and that water management is particularly focused on outcomes for the most vulnerable.
- Environmental justice: The environmental justice (EJ) movement is rooted in the insight that systemic racism and other deep-rooted societal forces have strongly influenced both the ability of different groups to participate in environmental decision making and the distribution of environmental harms and benefits. EJ initially focused on the location of hazardous waste sites, finding that they were disproportionately sited in neighborhoods of color, and has since expanded to include questions of water access and water quality, among other environmental issues. EJ recognizes that historical patterns of segregation, migration, racism, and underinvestment are reflected in today's environmental impacts and health outcomes, and it encourages us to use the lenses of race, gender, culture, and identity to understand power differences and how they manifest in water management.

4.2. Sustainability

We are using the term *sustainability* loosely to refer to the incorporation of ecological health as a water management goal. At the risk of oversimplifying, we can identify two distinct reasons that we might consider this an important goal, reasons that have their roots in the early-twentieth-century debate between ***conservationism*** and ***preservationism*** in the United States.

- Enlightened self-interest: The conservationist ethic—articulated by Gifford Pinchot (1865–1946), among others—saw nature as a resource to be exploited for the benefit of humanity but was concerned about the destruction of that resource by improper management, especially overharvesting, erosion, and pollution. Pinchot added a sustainability element to the utilitarian maxim, calling for "the greatest good for the greatest number *for the longest time*." Today's incarnation of conservationism might be best articulated as a form of enlightened self-interest, which sees the good of humanity as the primary goal but also understands that humanity cannot survive without intact, functioning natural ecosystems. The modern version of conservationism also recognizes that people need nature in ways that go beyond the physical, including spiritual, emotional, and communal needs for connection to healthy ecosystems.
- The community of nature: The preservationist ethic—articulated by John Muir (1838–1914), among others—posited a moral duty to protect nature for its own sake, not just for the benefits it provided to humans, and argued for the preservation of wilderness as a place for nature to thrive. We now understand that wilderness is not truly separate from people, both because of our global impact and because people have been actively managing "wild" places for many millennia. Still, many modern environmentalists share Muir's sense that the duty to protect ecosystems is not just about protecting their value to humans. There are many variants of this belief, each providing a different framework for reenvisioning our relationship to nonhuman species and ecosystems. Some focus on the beauty of nature as a moral good to be preserved, some speak of the moral (and potentially legal) standing of nonhuman beings and even inanimate objects, and some see people as members of a larger natural community, with reciprocal relationships that make a claim on us. Many of these perspectives draw from indigenous traditions, which often see features of the natural world—and water in particular—as sacred, animate, and in relationship with people.

Clearly these two different versions of sustainability might have somewhat different implications for water management decisions, but in practice the differences are often small. To use the examples we presented at the start of this section, both of these perspectives would give significant weight—much more than in utilitarianism—to the endangered mussel, the fishing ground, the wetlands.

Does articulating a water ethic shed light on the nature of the global water crisis? I believe it does. I believe that many of the symptoms we described above (e.g., scarcity, pollution, population displacement, flooding, lack of access) reflect the fact that we have not paid enough attention to justice and sustainability. We have not thought hard enough about how the fruits of the hard path are distributed or who has had to pay the price for our engineering accomplishments. We have not realized that efforts to dominate nature will not have long-term success if they undermine the base of natural productivity on which all life depends.

This realization has led many to call for a ***soft path***, with a corresponding shift in both technologies and attitudes:

- Technologies: The soft path relies on ***green infrastructure*** or nature-based solutions: infrastructure that uses or mimics natural ecosystems and cycles and requires low inputs of external materials and energy. Soft-path infrastructure often brings benefits to local communities as well as the larger society.
- Attitudes: The soft path calls for working with, rather than against, the power of nature; for making room for water rather than constraining it; for restoring aquatic ecosystems rather than destroying them; for working collaboratively with communities rather than imposing external solutions.

Our challenge, then, is to combine the best of both paths: to synthesize the most promising features of ancient, modern, and emerging technologies to produce solutions that equitably satisfy human needs while protecting and respecting nature.

5. How We Get There: Infrastructure, Institutions, Incentives, and Information

If the previous section focused on clarifying *what* we want water management to achieve, this section starts our conversation about *how* to achieve those goals. We discuss four topics that we will return to throughout the book; each has played a role in creating the current water crisis, and each must play a role in achieving a just and sustainable water future.

Infrastructure: The issue of appropriate infrastructure has already featured prominently in our description of the hard and soft paths, and throughout the book we will explore the strengths and weaknesses of various water technologies, from dams (classic gray infrastructure) to water harvesting (a suite of green infrastructure approaches).

The water crisis reflects, in part, infrastructural failings:

- Gray infrastructure requires significant inputs of energy and materials during construction, operation, and decommissioning, thus contributing to climate change and other environmental problems. In addition, gray infrastructure often does serious damage to local ecosystems and communities (as when dams displace people and destroy rivers).
- When gray infrastructure fails (e.g., a levee is overtopped), "natural" disasters such as floods can do *more* damage than they would have done in the absence of that infrastructure.
- While we have relied too heavily on certain types of gray infrastructure (e.g., dams and levees), we have also not built enough urban water infrastructure (pipes, treatment plants) to ensure safe water and sanitation access for all, especially in rapidly growing slums.
- In many cases, we have not kept up with infrastructure maintenance and are now footing the bill for much-needed repairs.

How do we find the right mix of hard and soft infrastructure and ensure that we pay attention to maintenance as well as construction? We will come back to these critical questions.

Institutions: Infrastructure is only part of the picture. Equally important is water governance: the institutions and rules that determine what infrastructure is built, how it is managed, and how its benefits and costs are distributed.

The water crisis reflects, in part, the weaknesses of our water governance systems:

- Our rules for water use—many of them legacies of previous centuries—are not fair, sustainable, effective, or adaptable.
- The very centrality of water to every aspect of life means that many different agencies are involved in water governance: agencies with conflicting agendas and overlapping spheres of influence, often pulling in different directions.
- We don't do well at integrating across various parts of the hydrologic cycle, so we treat different water problems in isolation.
- We lack holistic and visionary planning; our reactive management style solves each emergency by laying the groundwork for the next one.
- Water governance is traditionally expert driven and undemocratic.

Can we reform our water institutions to align them with our goals of justice and sustainability? Can water governance become more effective, democratic, and integrated? Can we solve multiple problems at once by seeing various water flows (rain, runoff, drinking water, wastewater) as part of One Water? Stay tuned.

Incentives: Since water touches every aspect of our economy, most "water managers" are the individuals or companies who use water—and whose choices about how much water to use are affected by price (as well as other incentives). If we want people to make choices that are compatible with justice and sustainability, we need to harness the power of the marketplace to ensure that those choices are incentivized. The water crisis reflects, in part, the perverse incentives imbedded in water prices:

- Prices are signals of value. The price paid by a water user should reflect the ***opportunity cost*** of that water: its value in other uses, such as supporting a healthy ecosystem. But a healthy ecosystem is a ***public good***—one that everyone can benefit from—so it is consistently undervalued by the market. Thus, the cost of water does not reflect the value of the ecosystem, and the destruction of the ecosystem is an ***externality***—a cost that is not borne by the water user and so is not considered in deciding how much water to use.
- Even when different human uses are competing for the same limited water supply—so scarcity should in theory drive up the price—water prices are kept artificially low for complex historical, economic, and social reasons. Thus, those who are lucky enough to have water rights often use that water wastefully because they are paying nowhere near water's true cost.
- At the same time, the simple economic prescription—raise water prices—runs up against the equally simple objection: Affordable water is a basic human right.

Can we raise the price of water to better reflect scarcity and the value of water to ecosystems, while ensuring that this basic necessity is affordable to everyone? What types of market and nonmarket mechanisms can we use to square these two goals? How can the value of water be felt and expressed in nonmonetary ways as well? To be discussed.

Information: Without discounting the importance of values, it is also true that some of the most important questions of water management are empirical, not normative: To what extent do reservoirs release greenhouse gases? What types of flows do various fish need to survive and reproduce? What levels of various pollutants are safe for people? How is climate change affecting water availability? These are the questions that science is good at answering, and we need our water management to be informed by the best available science. Indeed, this book delves deeply into the latest scientific findings, and we will frequently turn to data to answer important questions. But we also need to heed Aldo Leopold's admonition that "to keep every cog and wheel is the first precaution of intelligent tinkering"[13]; our understanding of complex ecological systems is inevitably incomplete, so we should err on the side of protection.

The water crisis reflects, in part, our limited understanding of the consequences of our actions:

- We failed to see that building dams would break rivers into disconnected fragments and destroy the biological and economic productivity of those rivers.
- We somehow didn't get that diverting water from rivers would lead to salinization and drying of wetlands, lakes, and estuaries, loss of fisheries, and cultural and health impacts on local communities.
- We didn't understand that building levees to protect riverside communities from flooding would increase flood damage by taking away natural flood valves and by encouraging development in flood-prone areas.
- We ignored the buildup of greenhouse gases in the atmosphere and failed to fully grasp how climate change would exacerbate both drought and flooding.

Can we learn humility from these failures without giving up on using science to inform management? Can we draw on theory and data to make water management decisions while also incorporating the ***precautionary principle***? Let's find out.

Chapter Highlights

1. The ***Great Acceleration*** that we have experienced in the modern era has brought much good to humanity, but its benefits have been unevenly distributed, and our growing impact on the natural world threatens our well-being and that of our fellow travelers on this planet. We urgently need a Just Transition to sustainability.
2. Water management has been a central player in the creation of modernity and must also be central to the Just Transition.
3. Water is simultaneously a human right and an economic resource, two characteristics that are sometimes in tension.
4. As a resource, water has unique properties that affect how we manage it: It is ***renewable***, ***fugitive***, largely nonsubstitutable, and highly variable in space and

time. We draw on it for both ***instream*** and ***offstream*** uses, in both ***consumptive*** and ***nonconsumptive*** ways.

5. Water is closely linked to other resources such as energy and food. Unlike those resources, water is not traded globally, so the focus of water management is largely local, although factors such as climate change and ***virtual water*** make water a global issue as well.
6. Water is central to ***sustainable development*** and features prominently in the ***Sustainable Development Goals***.
7. The global water crisis is really a set of interconnected crises: flooding, scarcity, inequitable access, health impacts, population displacement, water conflict, and ecosystem degradation.
8. Modern water management has been dominated by the ***hard path***, reflecting an underlying ethic of ***utilitarianism***. The global water crisis calls on us to incorporate justice and sustainability into our water ethic.
9. In the past, communities of color and low-income communities have often borne the impacts of water infrastructure without fully sharing in its benefits. Justice requires that we work toward a fairer distribution of costs and benefits, along with fuller participation of affected communities in water decision making.
10. The early-twentieth-century debate between ***conservationism*** and ***preservationism*** provides a template for two attitudes toward sustainability: enlightened self-interest and membership in the community of nature. In either case, utilitarianism must be supplemented with a concern for healthy ecosystems.
11. To achieve our goal of just and sustainable water management, we need to pay attention to four factors that have contributed to the current crisis but can be harnessed for a better future: infrastructure, institutions, incentives, and information.

Notes

1. Kimmerer (2013).

2. Greeley (2017).

3. This second feature makes water different from renewable resources such as fisheries and timber, whose supply in a given time period depends on the amount of reproducing stock in the previous time period.

4. Grey and Sadoff (2007).

5. https://www.un.org/sustainabledevelopment/water-and-sanitation/; https://www.sdg6data.org/en/node/1; and https://www.un.org/millenniumgoals/environ.shtml.

6. Tickner et al. (2020).

7. https://www.livingplanetindex.org/latest_results.

8. Zhang et al. (2020).

9. Tickner et al. (2020).

10. Costanza et al. (2017).

11. https://teebweb.org/.

12. Costanza et al. (2014).

13. Leopold (1949).

Part I

Water Availability and Use: Supply and Demand, Scarcity and Change

The four chapters in Part I provide an overview of water as a resource for human use, addressing basic questions about *supply* (how much water is available and how that varies over space and time), *demand* (how much water we are using and for what purposes), and *scarcity* (the gap between supply and demand). A central theme of these chapters is that water supply is not a fixed quantity but rather is affected by both natural variability and anthropogenic factors, including land-use change, climate change, and water use itself.

We start in Chapter 2 with an analysis of water stocks and flows, paying special attention to the spatial and temporal variability in flows and to the hydrologic tools—largely rooted in the concept of "stationarity"—that are used to quantify that variability. Chapter 2 also includes a discussion of the megadroughts that have been discovered in the paleoclimate record, a discussion that ultimately leads us to question the stationarity model. Chapter 3 further undermines the stationarity model by discussing the two contemporary large-scale drivers of changing water availability—climate change and land-use change—and their implications for water management and planning. Chapter 4 turns to the demand side, with a brief history of how people have used water over the last 10,000 years, a more detailed discussion of the last hundred years or so, and a quantitative look at how much water we use for what purposes; this involves delving into some important definitional issues, including the concept of water footprints. Chapter 5 defines scarcity, introduces various scarcity indicators, identifies where scarcity is (and isn't) a problem, and examines the phenomenon of *depletion*: rivers, lakes, and aquifers where human water use has changed the amount and timing of water availability, with significant impacts on both communities and ecosystems.

2

Water Availability: Spatial and Temporal Variability

- How much water is available for human use, and how does this vary across the world?
- How do floods and droughts affect water availability?
- What can we learn about drought from the paleoclimate record?

In this chapter, we define what we mean by water availability and analyze that availability globally and regionally. A critical consideration in this discussion is the uneven spatial and temporal distribution of water resources. We spend some time on tools for describing hydrologic variability and introduce the concept of stationarity. We then turn to understanding the causes and impacts of droughts, including past megadroughts, which leads us to question the utility of the stationarity model.

This chapter assumes some familiarity with hydrology. If you find that you need to strengthen or refresh your background, visit the companion website at https://watermanagement.yale.edu. Remember that terms in ***bold italics*** are defined in the glossary, and a guide to units and conversions is provided at the beginning of the book.

1. Global Stocks and Flows

Discussions of global water resources often begin with the volumes of water in various environmental compartments, referred to as water stocks. These numbers (Table 2-1) reveal that our "water planet" is, of course, mostly saltwater, which supports a great abundance of life but is unsuitable for human use and thus not considered part of the water "resource." Still, even excluding saltwater and frozen water, the earth has large volumes of freshwater, mostly in the form of lakes and ***groundwater***.

However, a focus on stocks is misleading, because water is a ***renewable resource*** that is continually replenished through the hydrologic cycle. The large stocks of water in ***aquifers*** and lakes may present tempting targets for water use, but if that water is not being replenished (or if we are using it more rapidly than it is being replenished), then we are depleting the stock and it will eventually run out. If we want to achieve

Table 2-1. Estimates of water volumes in various stocks (in thousands of km^3). Data from Abbott et al. (2019), except for groundwater data from Ferguson et al. (2021).

Saltwater	
Oceans	1,300,000
Saline groundwater	28,000
Saline lakes	95
Freshwater	
Liquid	
Fresh groundwater[a]	15,900
Fresh lakes	110
Soil moisture (green water)[b]	54
Wetlands	14
Reservoirs	11
Rivers	2
Solid and Gas	
Glaciers	26,000
Permafrost	200
Atmosphere (water vapor)	13
Snowpack (annual maximum)	2.7

[a] The fraction of global groundwater that is fresh is poorly known; here I assume that groundwater in the top 1 km of Earth's crust is fresh, while groundwater below that level is saline. This probably overestimates the volume of recoverable fresh groundwater, both because the fresh/brackish transition is shallower than 1 km in many locations and because it is usually not economical to extract groundwater from deeper than a few hundred meters.

[b] The ***green water*** held in soil pores is available to plants, but—in contrast to the ***blue water*** in rivers, lakes, and aquifers—it can't be transported from its location for other uses, such as drinking.

sustainable water use, our emphasis should be on flows: the conversion of water vapor to precipitation and ultimately to streamflow. To put it slightly differently, rivers—despite their small volume—are of particular importance to water managers, because they are the primary mechanism for the renewable flow of liquid freshwater.

Figure 2-1 shows estimated water flows at a global scale. Evaporation from the ocean (450,000 km^3/yr) is greater than precipitation over the ocean (404,000 km^3/yr). The difference of 46,000 km^3/yr is transported as atmospheric water vapor to the continents, where it contributes to an excess of precipitation over ***evapotranspiration***. This excess precipitation then flows as ***runoff*** back to the oceans, completing the cycle. It is this runoff—the flow back to the ocean of 46,000 km^3 of freshwater—that constitutes the renewable water resource that is potentially available for human use year after year (although it should be clear that appropriating *all* this flow for human use would severely damage aquatic ecosystems). This dynamic is described by the basic water budget equation $P = ET + R$: precipitation (P) either returns to the atmosphere as evapotranspiration (ET) or becomes runoff (R).

This 46,000 km^3/yr of runoff consists primarily of river flow but also includes about 2,300 km^3/yr of ice discharge from Antarctica and a small amount (probably under 300 km^3/yr)[1] of submarine groundwater discharge (i.e., groundwater that

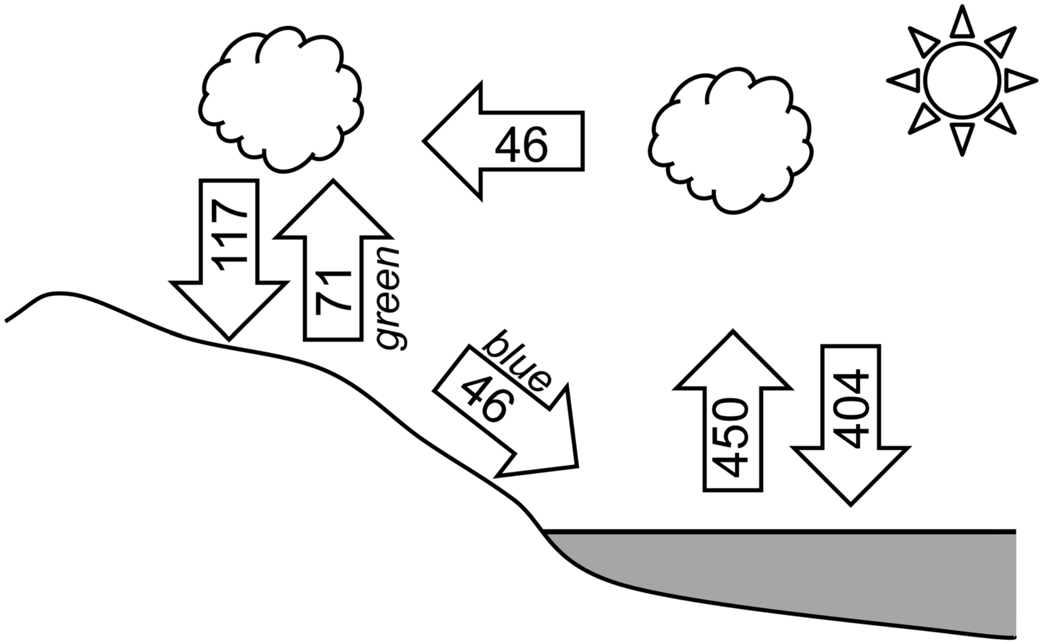

Figure 2-1. Simplified schematic of the global hydrologic cycle (units: thousands of km^3/yr). Upward arrows indicate evapotranspiration and downward arrows indicate precipitation. Lateral arrows indicate water vapor transport from oceans to continents and water runoff from continents to oceans. Data from Rodell et al. (2015).

discharges directly to the oceans). In addition, much of the world's river flow has spent some time as groundwater before reaching the river. That is, we can think of ***groundwater recharge*** (~16,000 km^3 per year)[2] as a component of renewable runoff, but since most of that recharge ends up discharging to rivers and becoming streamflow, we should be careful not to double-count it.

Several caveats apply to Table 2-1 and Figure 2-1:

- Our knowledge of the global hydrologic cycle is improving but is still incomplete, and there are substantial uncertainties in the values shown for both stocks and flows.
- Flows and stocks are changing over time, due to both natural and human causes; the data shown can be viewed as a snapshot in time representing roughly the first decades of the twenty-first century.
- Even within this time period, these data should be viewed as an average; the coefficient of variation of annual global runoff is about 3 percent[3] and is much higher for individual rivers or regions.

In addition to the 46,000 km^3/yr of runoff (blue water), we should also pay attention to the precipitation that does not become runoff but instead returns to the atmosphere as ET (71,000 km^3/yr). This green water flow supports the growth of terrestrial vegetation and is appropriated for human use when we grow crops using ***rainfed agriculture*** (as opposed to ***irrigation***, which uses blue water).

2. Spatial Variation in Water Availability

The global hydrologic cycle shown in Figure 2-1 has limited relevance to water managers, since water is largely a local resource. Water resources—whether they are stocks or flows, blue or green—are not evenly distributed around the world. Complex atmospheric and oceanic circulation patterns—driven by the differential heating of Earth's surface and the Coriolis force resulting from Earth's rotation—produce a global mosaic of climates, with great variation in the amount and timing of precipitation. The wettest areas of the planet are those where rising air produces intense rainfall, including a zone near the equator (referred to as the ***Intertropical Convergence Zone [ITCZ]***), where air is made buoyant by heating, and high mountain ranges (often referred to as ***water towers*** for their ability to capture and store water), where air is forced upward by topography. Of course, climate patterns are more complex than this simplification, as reflected in the east–west gradient in precipitation in the United States, with areas west of the 100th meridian being much drier than areas to the east.

A useful metric for quantifying local blue water generation is the ***aridity index*** (AI), defined as the ratio of mean annual precipitation (P) to mean annual ***potential evapotranspiration*** (PET, the amount of water that would evaporate under local climate conditions if the supply of water were not limited). A ratio greater than 1 means that there is "excess" water that can become runoff, while a ratio lower than 1 suggests that rainfall will evaporate without generating any blue water. In practice, since AI is based on annual averages, even areas with AI less than 1 can produce some runoff during the wet season, when P can be temporarily greater than PET.

A global map of AI (Figure 2-2) can be used to identify ***drylands***: areas with AI less than 0.65 and therefore little or no runoff generation. Drylands occupy some 41 percent of the land surface and are home to 38 percent of the global population.[4] Subcategories of drylands are dry subhumid (AI = 0.5–0.65), semiarid (0.2–0.5), arid (0.05–0.2), and hyperarid (less than 0.05). While drylands include desert biomes, they also include grasslands and savannas (mixed grassland–woodland biomes).

As a picture of available blue water resources, Figure 2-2 is misleading in one important way: It shows only local AI (and by implication blue water generation) but ignores nonlocal inputs of blue water. In reality, runoff generated in wetter areas is channeled through river systems, which can transport blue water large distances from where it is generated; the ***watershed*** or ***river basin*** (Box 2-1) is thus a critical spatial unit for understanding and analyzing runoff. For example, Cairo, which experiences essentially no precipitation or runoff generation, sits on the banks of the Nile River, which delivers large amounts of runoff generated in the wetter portions of the Nile Basin.

Taking into account all these factors, the most useful metric for blue water availability is ***total renewable water resources (TRWR)***, expressed in flow units (volume/time) and usually calculated on an annual basis. At the basin scale, this corresponds to average annual runoff (streamflow). At other scales (e.g., a country), it includes internally generated runoff but also external inputs of blue water from upstream.

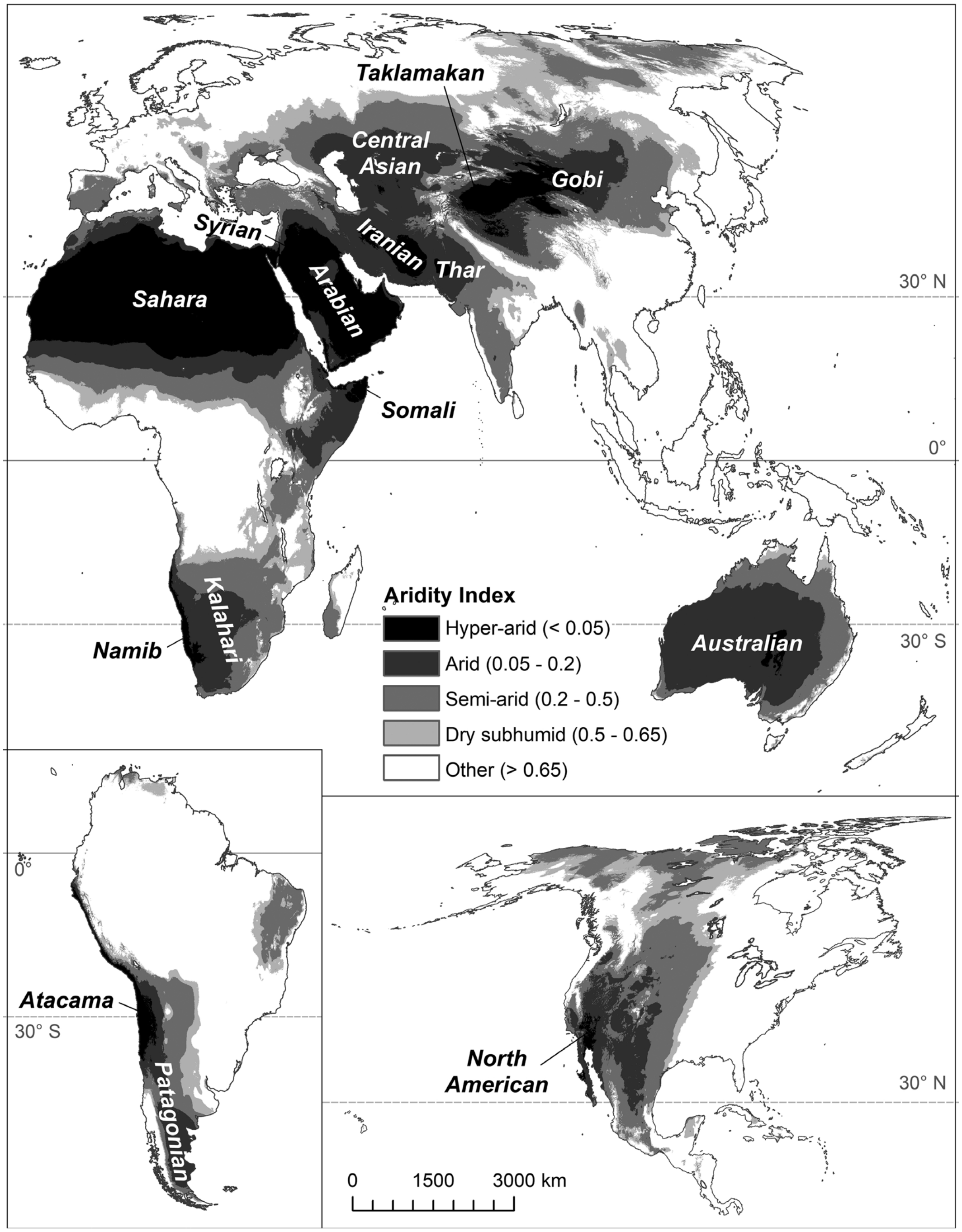

Figure 2-2. Global map of the aridity index, with major world deserts shown. Areas in white generate significant blue water runoff, while shaded areas do not. Map by Anna Yue Yu. Data from https://cgiarcsi.community/2019/01/24/global-aridity-index-and-potential-evapotranspiration-climate-database-v2/.

Box 2-1. Watershed Primer

A ***watershed*** can be defined as “the topographic area within which apparent surface water runoff drains to a specific point on a stream or to a water body such as a lake.”[a] In other words, the watershed defined by a given point is the land area that contributes water to that point. Watersheds are delineated based on surface topography, with the understanding that water that falls as precipitation will move downhill to the stream (perhaps entering groundwater temporarily on the way there) and then flow downstream past our selected point. Of course, not all the precipitation that falls in the watershed will become streamflow (some will undergo ET), but all the water that leaves the watershed in liquid form must flow past our point.

A river’s full watershed, often called a ***river basin***, is defined by its outlet—the point where it enters the ocean or other water body—but we can also define nested subwatersheds at other points along the river’s course (Figure 2-B1). To delineate the watershed for any point along a stream in the United States (and get flow estimates for that point), go to https://streamstats.usgs.gov/ss/. To see a visualization of the water flow pathway from any location in the United States, see https://river-runner.samlearner.com/.

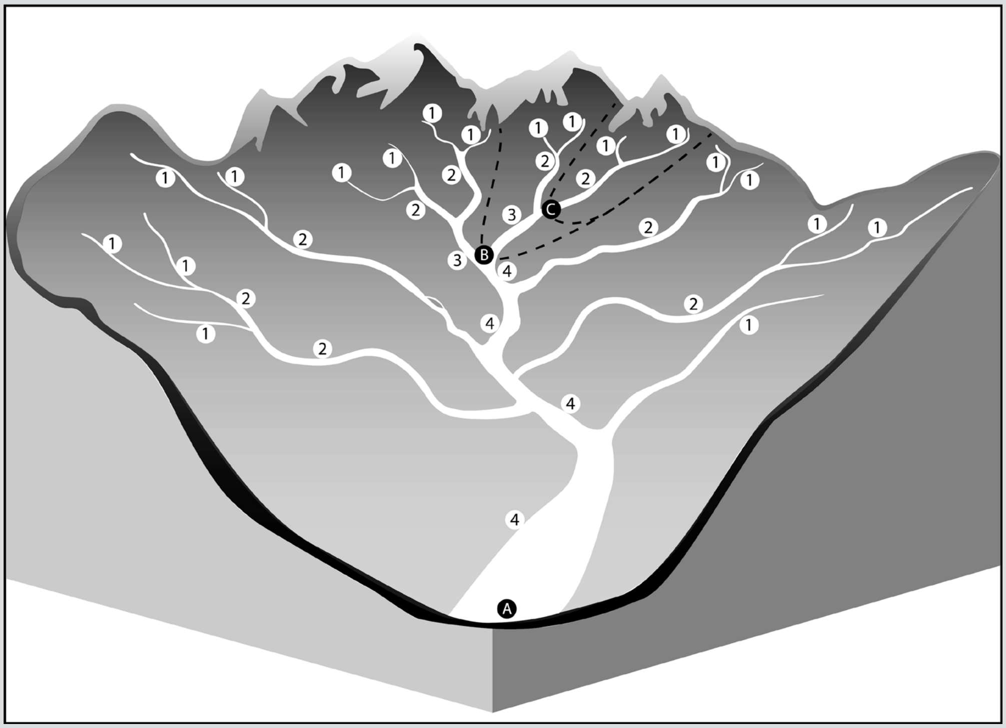

Figure 2-B1. The watershed defined by point A. In addition, two smaller subwatersheds, defined by points B and C, are also delineated. Watershed C is nested within watershed B, which is nested within watershed A. Numbers are Strahler stream orders, a measure of stream size. (To calculate Strahler stream order, follow these rules: The smallest perennial stream that is shown on the map is considered first order. Where two streams of equal order come together, the combined stream has an order that is 1 greater than each of its tributary streams. Where two streams of unequal order come together, the combined stream has an order equal to that of the higher-order tributary. In other words, in this version of math, 1 + 1 = 2 but 1 + 2 = 2.) Graphic by Maureen Gately.

Box 2-1 *continued*

The watershed has long been recognized by hydrologists and aquatic chemists as a fundamental unit of analysis. Rivers have been described as the blood vessels of watersheds, and river hydrology and chemistry have been seen as a watershed's vital signs, critical for assessing its health. The underlying insight is that rivers are affected—in their flow and their chemistry—by how land is used within their watersheds, which means that water management must also involve land management.

At the most basic level, the watershed is useful as a unit for water budgets. Since the only surface water flow across a watershed boundary consists of runoff at the outlet, the equation $P = R + ET$ can be applied at the watershed scale (but not at the scale of, say, a state). Two hydrologic parameters are often derived from this budget:

- The ***water yield*** (typical units: mm/yr) is simply the runoff from the watershed (average annual streamflow) divided by the area of the watershed.
- The ***runoff ratio*** (unitless) is the ratio of R to P and describes how efficiently precipitation is converted into blue water. Based on Figure 2-1, the global average runoff ratio is 46/117, or 39 percent.

Beyond the scientific convenience of the watershed, there are benefits to the watershed as a unit of management. First, water users within a watershed are, in the most fundamental way, sharing the same resource. Water that is used upstream is not available for use downstream. Pollution that is discharged upstream affects the quality of water downstream.

Second, the watershed is the natural unit within which anthropogenic movement of water has the lowest ecological and economic costs. When water is withdrawn from a stream and used within the same watershed, the return flow from that use (i.e., the portion of the water that is not consumed) remains within the watershed and ultimately flows back to the stream where it came from, thus reducing the ecological impacts of that withdrawal. In addition, it is often cheaper to move water within a watershed, since an ***interbasin transfer*** will require pumping water over the watershed divide (or tunneling through it).

Still, water managers recognize that the watershed is not the only relevant unit. Given the ubiquity of interbasin transfers and the fact that water agencies are defined by state or national boundaries—which generally do not align with watershed boundaries—water managers must be prepared to deal with multiple overlapping scales simultaneously.

Note

[a] Omernik and Bailey (1997).

3. Temporal Variation in Water Availability

In addition to the spatial variability discussed above, water availability also fluctuates dramatically over time, posing a critical challenge for water managers. In this section, we introduce several tools for describing hydrologic variability, while the next section focuses specifically on drought as an often devastating manifestation of this variability.

3.1. Hydrographs

Perhaps the most obvious way to examine variability in streamflow is to look closely at a ***hydrograph***, such as the one shown in Figure 2-3 for the Quinnipiac River (Connecticut) for water years 2014–2016. (A water year in the United States runs from October 1 to September 30.)

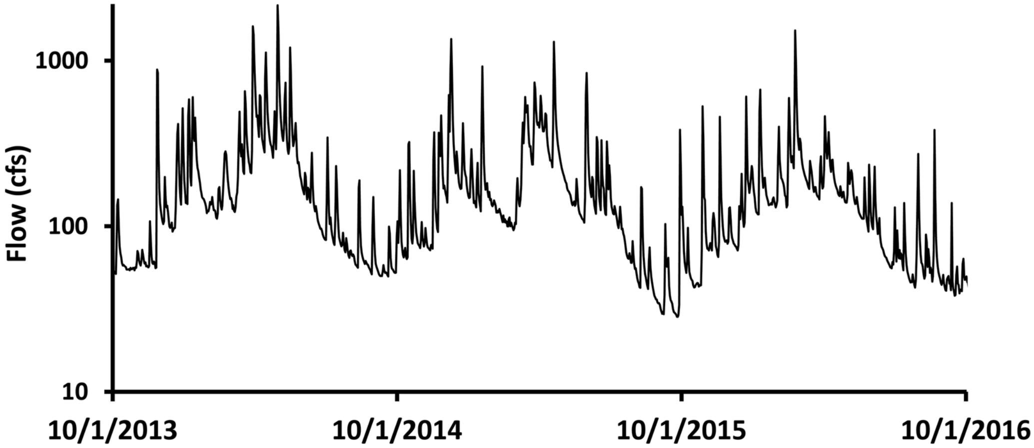

Figure 2-3. Hydrograph for the Quinnipiac River, Connecticut, for water years 2014 through 2016 (daily data). Baseflow can be envisioned as a smooth line running under the graph. Note the log scale on the vertical axis. Data from US Geological Survey (https://waterdata.usgs.gov/nwis/uv?01196500).

Figure 2-3 shows variation at three time scales:

- Storms: During storm events, flow rises rapidly in response to rainfall and then slowly declines. The time scale of the storm response is generally shorter for shorter rain events, smaller streams, and more urbanized watersheds. The flow of water in a stream in direct response to a storm event is referred to as stormflow, while flow between storm events is referred to as baseflow. The pathways by which water travels to the stream can be quite complex, but stormflow pathways are generally more rapid and closer to the surface relative to baseflow, which is fed by the slow discharge of groundwater.
- Seasonal: For the Quinnipiac River, precipitation is (on average) evenly distributed throughout the year, but flows are generally lower in the summer months because of higher ET. Other sites may show more extreme seasonal differences, either because of seasonality in precipitation (Box 2-2) or because precipitation accumulates as snow over the winter and then is converted to runoff in the form of a large spring snowmelt peak.
- Interannual: At longer time scales, flow varies in response to interannual variation in precipitation and temperature.

3.2. Flow Duration Curves

Despite the utility of hydrographs in identifying obvious patterns, we need statistical tools to quantitatively summarize long-term flow records. For example, if we want to use the Quinnipiac River to generate hydropower or to supply a town with a water source, it would be helpful to be able to say something like, "We can count on having at least *X* cfs (cubic feet per second) 95 percent of the time." That is exactly the logic of the ***flow duration curve*** (FDC), which plots how often different flow levels were equaled or exceeded (their ***exceedance probabilities***) in the period of record

Box 2-2. Monsoon Systems

The word ***monsoon***, as used in climate and water science, refers to a seasonal reversal of wind direction that drives a strong seasonal pattern in precipitation. Eight distinct monsoon systems can be identified: Indian, East Asian, Western North Pacific, Australian, North American, South American, North African, and South African. More than half the world's population lives in regions affected by these monsoons.

Perhaps the best-understood of these is the Indian Monsoon, which is driven by the seasonal movement of the ITCZ relative to the Indian subcontinent. In January, the ITCZ is located just south of the equator in the Indian Ocean, and winds over India blow toward this low-pressure zone, resulting in dry continental winds from the northeast and little precipitation for most of the country. By July, the Asian land mass has heated up more than the waters of the Indian Ocean, and the ITCZ moves north over the Tibetan Plateau. This draws in moist air from the Indian Ocean, resulting in southwesterly winds over much of India that can produce torrential rainfall as the air is forced upward by the Himalayas.

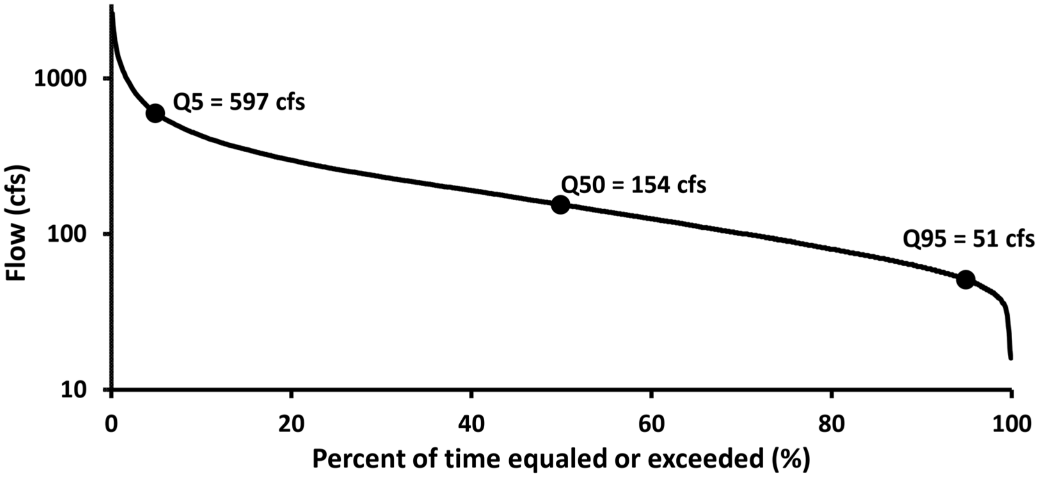

Figure 2-4. Flow duration curve, based on US Geological Survey daily flow data for the Quinnipiac River from 1931 to 2019.

(Figure 2-4). Monthly or seasonal FDCs can be used to understand typical patterns in different times of year.

Flow statistics can be directly read off FDCs; commonly used metrics include the following:

- Q95: the flow that is equaled or exceeded 95 percent of the time (i.e., the fifth percentile flow), often used as a measure of low-flow conditions;
- Q50: the flow that is equaled or exceeded 50 percent of the time (i.e., the median flow);
- Q5/Q95: the ratio of the 5 percent-exceedance flow to the 95 percent-exceedance flow; the higher this ratio, the greater the flow variability in the system.

3.3. Flood Frequency Analysis

What if we are especially interested in the risk of the highest flows? Since these flows are rare, an FDC is of limited utility, and we turn instead to an approach known as ***flood frequency analysis***. Like an FDC, flood frequency analysis uses past data to predict the likelihood of future flows, but unlike an FDC, it uses only the highest flow for each water year in the period of record. Using these peak flow data (and certain statistical assumptions), we can estimate the annual probability (p) that a river will exceed a certain flow level. For example (Figure 2-5), the Quinnipiac River has a 1% annual probability of reaching a flow of at least 6,663 cfs and a 50 percent annual probability of reaching a flow of at least 2,214 cfs.

The ***recurrence interval*** for a flood of a given magnitude is defined as $1/p$ (i.e., the inverse of the annual exceedance probability). Thus, a flood with an annual exceedance probability of 1 percent (0.01) is the hundred-year flood, a flood with a probability of 50 percent (0.5) is the two-year flood, and so on. Importantly, the phrase "hundred-year flood" is not meant to convey that a flood of this magnitude will occur like clockwork every hundred years. Rather, it indicates that a flood of this size (or larger) has a 1 percent chance of occurring in any given year, regardless of what has happened in previous years (since each year is assumed to be independent of the previous year).

The logic of flood frequency analysis can also be used to characterize low-flow events, most commonly through the 7Q10, defined as the seven-day average flow with a ten-year recurrence interval. For example, if the 7Q10 is 50 cfs, there is a 10 percent chance that the lowest seven-day average flow of the year will be 50 cfs or lower.

Both the flow duration curve and the flood frequency analysis are based on an important assumption: that the past is a good guide to the future. Put more formally, these tools (and others widely used by hydrologists) assume that a hydrologic variable such as flow is a random variable with a nonchanging ***probability density function*** (PDF) that can be determined from existing hydrologic data. For example, in the case of the flood frequency analysis shown in Figure 2-5, we are assuming that each year in the future will be a random draw from the PDF shown in Figure 2-6. Note that this assumption of ***stationarity*** recognizes hydrologic variability and even recognizes that there is uncertainty in the PDF, since it is based on limited data, but assumes that the underlying pattern of variability is not systematically changing over time. Is this assumption of stationarity a valid one? We will discuss this further at the end of this chapter and in Chapter 3.

One conservative alternative to flood frequency analysis is to estimate the probable maximum flood (PMF), defined as the maximum flood that is likely to occur in a given area under the most extreme conditions. This is derived from the probable maximum precipitation (PMP), estimated by meteorologists based on the maximum amount of moisture that the atmosphere can hold; the amount of the PMP that will run off to form the PMF is then estimated based on watershed soils, land use, and topography. The PMF is typically used in situations where a conservative estimate of possible flooding is needed, such as in dam safety design.

3.4. Rainfall Intensity–Duration–Frequency Curves

Temporal variability in precipitation can be treated similarly to the variability in streamflow discussed above, with two additional complications. First, unlike streamflow—which is relevant only in certain parts of the landscape (rivers)—precipitation falls everywhere, so we would ideally like to have point estimates of precipitation variability for every location of interest—but these estimates must be constructed from

(continued...)

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