CHAPTER 15

California's Water Footprint Is Too Big for Its Pipes

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How much water do you use in a day? Let's start with this morning. If you took a five-minute shower you probably used about ten gallons, then three or four more gallons to run the faucet and flush the toilet. At breakfast, maybe you heated a few cups of water to brew your coffee or tea. This doesn't seem like much so far, but before we move on, let's look into our cups and steep our minds in how much water really went into this warm infusion. What about the water needed to grow the coffee beans—should we count that? It turns out that it takes more than a thousand times as much water to grow and prepare the beans as it does to brew the coffee. That's a week's worth of showers for an eight-ounce cup of coffee. Tea turns out to be about a quarter as water-intensive as coffee.

We start from the standpoint that, yes, all that water should be counted; not on our monthly water bills, but toward our individual and collective *water footprints*. Your water footprint is the total amount of water required to support your lifestyle—to grow all the food you eat, to make the clothes and other goods you use, and to produce the energy to power your home and means of transportation. And it's probably bigger than you think. If you live in California, your water footprint is (on average) about 1,500 gallons per day, more than ten times the state's per capita daily amount for direct use through piped delivery (that's for showering, watering the garden, etc.). That average is about the same for the rest of Americans but is nearly double the global average of about 800 gallons per capita daily (GPCD). Worldwide, people's water footprints vary widely depending on their habits and the societies they live in. The average water footprint in other developed countries is about 1,000 GPCD, while the average in China is about 600 GPCD.

Our individual and collective water footprints have important implications for sustainability, which we define on a global level as the capability of current and future generations—in other locations and of other species—to meet their social, economic, and ecological needs. It is crucial that sustainability be defined on a global level because of the increasingly interconnected nature of people and resources worldwide. Thus, when we think about the major challenges of water management in the twenty-first century—what has been called the *global water crisis* (see UNDP 2006)—we see a relationship between observations "over there" and actions "over here," in places like California. Water footprint assessments provide a framework for understanding these relationships. For California, because many of the goods consumed come from other places, improving water footprint sustainability entails considering impacts on social and ecological systems both within and beyond its borders.

As individuals, understanding the water implications of our daily habits and decisions can help us live less resource-intensive lifestyles. At larger scales, when we add up people's cumulative water footprints, there can also be implications for water resource management and planning. Multiply 1,500 GPCD by 38 million Californians and we see that over 20 trillion gallons of water are needed each year to support the state's population. That's more water than would flow unimpaired down all the state's rivers, meaning without diversions for human use (California Department of Water Resources 2014). In other words, if California tried to produce everything that it consumes within the state's borders, there wouldn't be enough surface water to do so. California has outgrown itself, and is becoming more and more dependent on water from elsewhere. Our collective water footprint is truly global. The sustainability of California's future social and natural systems depends on how sustainably water resources can be managed inside and outside its borders.

This chapter discusses California's water footprint from our particular perspectives on water sustainability. Though we each come from more focused disciplines—engineering and ecology—here we take an integrated and macroscopic approach to looking at sustainability in California, that is, from a statewide perspective while acknowledging global connections. We see relevance in our analysis for actors at all levels of decision-making, from individual residents, to businesses, to local and state planners. Water affects and is affected by everything we do as a society, and we are all connected by it. The methods we use provide a framework that helps in understanding the nature of these connections. It is a relatively new method that we try to present as transparently and reflexively as possible to help improve its relevance in sustainability science.

In the second section we work through the science of water footprint assessment: what it tries to measure, why, and how. In the third section we present a case study of California's water footprint, including what and where it relates to, and how it has changed over time. In the fourth section we reflect on the degree of uncertainty in the information that our assessment provides, as well as what is needed to improve certainty in the processes we are attempting to study. Lastly, we discuss what we see as the implications and possible applications of water footprint science for various actors in California, as well as possible responses.

WATER FOOTPRINT SCIENCE

So far we have introduced the water footprint as both a concept and a number: the quantity of water required to produce the things that we consume. But how does that number relate to actual water sustainability challenges, both within California and elsewhere? After all, a "footprint" is about more than just its shoe size; every foot makes a different print depending on its size, weight, and shape, as well as the place it is stepping on. With water, then, what would we want a footprint assessment to tell us about the impacts those gallons have on sustainability concerns? To begin answering this question, we need to review the hydrologic cycle, thinking about how people and ecosystems engage with it and experience it.

From previous classes, you may recall the standard description of the hydrologic cycle (or just the "water cycle"). Solar energy drives evaporation from oceans and lakes, as well as transpiration from plants on land, accumulating water molecules in the atmosphere until they condense and fall as rain, sleet, or snow—which, when it falls on land, eventually flows as ground or surface water back to the sea through river basins (figure 15.1). Globally, this cycle operates on a fixed budget of water: about 1.4 billion cubic kilometers. While this may seem like a lot, currently less than one one-hundredth of 1 percent is readily available freshwater; the rest is locked up in ice, seawater, and inaccessible groundwater (Shiklomanov 2000).

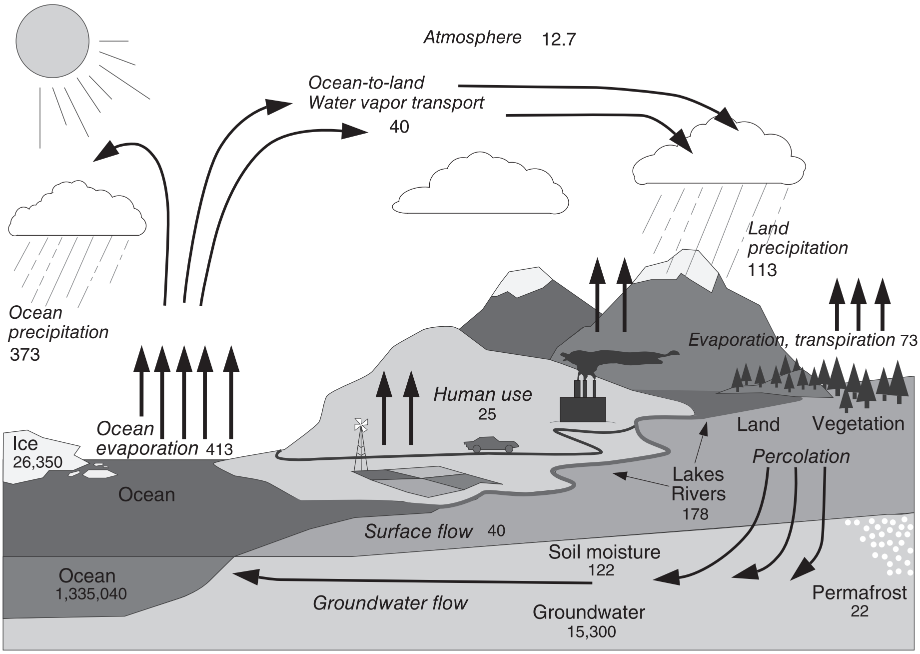

FIGURE 15.1. Simplified global water budget. Stocks in thousand cubic kilometers, flows in thousand cubic kilometers per year. Adapted from Trenberth et al. (2007).

While this may all sound familiar, notably missing from the standard description are the ways that humans and animals modify the stocks and flows of Earth's water. Human societies have always engaged with and modified the hydrologic cycle through their activities. Figure 15.1 depicts some of these activities—groundwater pumping for agriculture and industrial uses—though notably missing are domestic systems, as well as dams, canals, and other infrastructure that alters the hydrologic cycle in order to sustain human populations. People also modify the hydrologic cycle indirectly through land-use practices like urbanization, and most notably, by emitting massive amounts of greenhouse gases that cause global warming (see chapter 1, this volume).

Human activities that use water, depicted at the center of figure 15.1, make use of about a quarter of available freshwater annually, through rain-fed agriculture and pasturage, ground and surface water withdrawals, and in-stream uses such as transportation and waste assimilation (Postel, Daily, and Ehrlich 1996). These uses can be thought of as alterations or temporary interventions in the hydrologic cycle, since the water is ultimately put back into the cycle through evaporation, transpiration, or return flow. These interventions, while seemingly small in the global scheme, can have dramatic effects at the scale of a river basin when they are continuous or large relative to available flow patterns. This is particularly important because the river basin is the scale where people, plants, and animals grow and depend on water, a point we will return to later.

When water is withdrawn for human use, the term *consumptive use* refers to the portion of water that is made unavailable for reuse in the same basin, either through evaporation or transpiration (together, *evapotranspiration*) or through contamination (Gleick 2003). For example, in California, when a farmer draws water to irrigate his or her field, the portion that is evapotranspired is considered consumptive use because it is more likely to fall as rain somewhere much further east, like the Great Plains. The portion that returns to ground or surface water can also be considered consumptively used if it is contaminated with pollution to levels that exceed regulatory limits. Industrial processes like canning, making paper, manufacturing electronics, and producing electricity also use water for a variety of purposes that can result in consumptive use through evaporation and contamination.

In measuring the water footprint of any product (agricultural, industrial, etc.) we include only the consumptive portion of water use, since uncontaminated return flow can be used for other purposes in the basin. The water footprint accounting scheme divides consumptive use into three components, represented by three colors: blue, green and grey. *Blue water* is the managed surface and groundwater that flows through rivers, aqueducts, and pipes to where it is used, at homes, parks, factories, and farms. This is the water that we see; it has been described as more "charismatic" than less visible green water (Schneider 2013). *Green water* is the precipitation and soil moisture used directly by plants without being collected and applied by users. *Grey water* (not to be confused with graywater, discussed in chapter 14) is an indicator of contamination from a production process and is defined as the quantity of water needed to dilute pollution to levels that are not harmful to ecological and social needs (which may or may not correspond with regulatory standards).

The three water footprint components have different implications for sustainability in the location where water use occurs. Blue water, because it can be used for several alternative purposes, has an opportunity cost for each use. In other words, we should ask: What else could that water have been used for? In California, for example, blue water allocation often pits competing uses against one another, whether agricultural, urban, or environmental. Additionally, blue water typically has financial costs for treatment, pumping, or other infrastructure. Green water, on the other hand, is used directly on agricultural land, so it is important insofar as that water becomes unavailable for other land uses, alternative crops, or native vegetation. Changes in green water use can also affect blue water availability, and vice versa.

Grey water accounts for water quality impacts in a watershed, but it is an indicator estimate rather than a measurement, since it tells us how much additional water *would* be required to meet regulatory standards, regardless of whether that dilution actually occurs. In reality we would expect a farm, municipal waste discharger, or factory to figure out how to release less pollution rather than use more water to dilute it (though this does happen). While many water footprint practitioners add up blue, green, and grey water, we choose to report grey water separately from blue and green, so as not to double-count contaminated grey water as downstream blue water use. Still, grey water footprints provide an important indicator of the impact of production processes on water quality.

From a sustainability perspective, it is important to identify not just the different components of water use but how those types of water affect present and future conditions for social and ecological systems at the river-basin scale. Basins with fewer people and more water will likely be less impacted by consumptive water use than areas where larger populations already use much of the available water. Each river basin has its own particular issues related to blue, green, and grey water. The challenge for assessing the sustainability of water footprints is then to trace how much, what type, and where water was consumptively used, and to relate those uses to ongoing socio-ecological challenges at the river-basin scale. While this is a complex task, often deserving of a case-study approach, other methods exist that use indicators or combinations of indicators to help researchers understand the relative impacts and risks of water footprints at the basin scale. Examples of these indicators include the Watershed Sustainability Index (Chaves and Alipaz 2006) and the Water Poverty Index (Sullivan, Meigh, and Giacomello 2003).

Blue, green, and grey water footprints can also occur at multiple stages in making a product. Returning to the cup of coffee and the thousand cups of water required to make it, most of it was probably green water used by the coffee plant, since most coffee farming is mostly rainfed. Some of it, however, was probably blue water used (consumptively) to

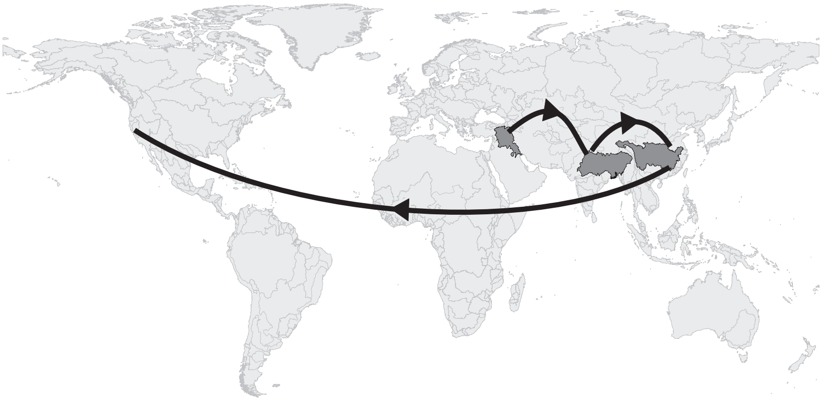

FIGURE 15.2. Water footprints can have impacts in multiple river basins. For example, here is the hypothetical supply chain of a cotton T-shirt, with impacts in the Tigris-Euphrates, Ganges-Brahmaputra, and Yangtze river basins.

remove the pulp from the bean and for other wet-processing steps. Other products, like cotton clothing, may require water at many more steps, from green water on the farm, to blue water at the factory for washing and dyeing fabrics, which may in turn also create grey water footprints. Industrial products like electronics require water for mining metals and manufacturing parts like semiconductors, and often have grey water impacts as well. Energy sources also entail mining fuels like oil and gas, but even more blue water is required for cooling at thermoelectric power plants.

These production stages can also take place in multiple locations, with differing impacts on river basins in far-off places. For example, cotton for a T-shirt purchased in a California shop might have been grown under rainfed conditions in India, processed into cloth and washed with municipal water in Bangladesh, then shipped to China, where further processing and dyeing may impact the water quality of a nearby river, before being finished and taken to market. Such a T-shirt would have a green, blue, and grey water footprint covering three different countries and many river basins (see figure 15.2). On average, a single T-shirt requires 290 gallons of green water, 320 gallons of blue water, and 100 gallons of grey water from river basins around the world (Chapagain et al. 2006).

Production in different locations can also be more or less efficient depending on production conditions, methods, and technologies; so the geographic routing of a product's supply chain can make a big difference in its overall water footprint. For example, the water footprint of a cotton

T-shirt made with U.S. cotton is about one-fourth the size of one made with Indian cotton (Chapagain et al. 2006). Globally averaged water footprints have been calculated for a range of products using United Nations agricultural and industrial water-use statistics, which are in turn derived from regional surveys and models. These results have been worked into several useful online tools for comparing the average water footprints of products and estimating one's individual water footprint based on personal diet, habits, and income (see www.waterfootprint.org).

National differences in production and consumption can also provide more detailed information about the water footprints of products and people. National production and trade statistics (also from the United Nations) indicate whether a product was likely produced domestically or imported, and from where. Using this information, the water footprint has been calculated for nearly every country, including the United States, allowing us to compare per capita water footprints as we did in the beginning of the chapter. However, within larger countries like the United States, we may expect regions and states to have different water footprint dynamics. Therefore, we use more locally tailored production and trade statistics to evaluate California's water footprint, which we turn to in the next section.

WATER FOOTPRINT AND CALIFORNIA

Data that may be used in calculating California's water footprint include state-level statistics on production of agricultural and industrial goods, surveyed and modeled information on how much water was consumptively used to make those goods, and trade statistics on whether those products were exported to other states or countries. If goods are not exported we assume that they are consumed and count toward California's water footprint. We also account for imported goods and the water footprint associated with their production in the country from where we import them. Goods that are imported and re-exported (which happens a lot in California ports) do not count toward California's water footprint. These readily available data sources allow us to calculate a first approximation of California's water footprint.

Before we present the results, we consider why a water footprint assessment might be important for a state like California. Historically, California has had a relationship with water that is unique among U.S. states. Given the temporal variability of its Mediterranean climate, combined with the geographic variability of its rainy north and desert

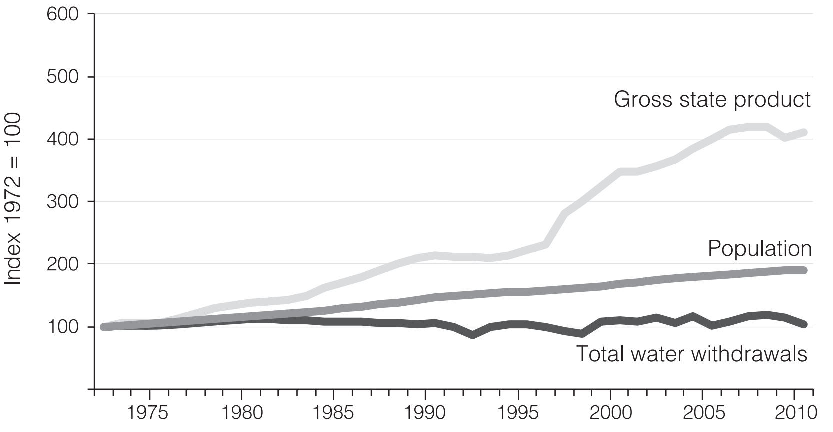

FIGURE 15.3. Trends in California's real gross domestic product, population, and freshwater withdrawals, 1972–2010. State-level real GDP is only available after 1986. GDP for 1972–1986 was estimated using a national-level inflation index. These data were collected by Department of Water Resources staff from older versions of Bulletin 160 (for 1972–1985), annual reports prepared by district staff (for 1989–1995), and the Water Portfolio from *California Water Plan Update 2013* (for 1998–2010). Sources: California Department of Finance (2011); California Department of Water Resources.

south, the management and manipulation of water flows have been integral to California's development and identity. Yet, as the state has grown to have the largest population in the nation and one of the highest-valued economies in the world, data show that total water withdrawals in California have remained relatively stable over the past 30 years (figure 15.3). This apparent "decoupling" of water use from population and state gross domestic product (GDP) growth raises two fundamental sustainability questions: How has growth in California been sustained? And can it be sustained in the future?

Regarding the first question, one answer is that Californians have come to use water in the state to do the things we want it to do much more efficiently. Indeed, to some extent, these trends reflect the adoption of more efficient technologies and practices by nearly all sectors of society, from households and businesses to farms, factories, and power plants (Gleick, Cooley, and Groves 2005; Rich 2009; Hanak et al. 2012). Many of these efforts have come about through technological innovation, strong policy, and behavioral change. All of these factors play roles and are interrelated in determining statewide water use and the management of California's water resources. Future water use within the state will continue to depend on these factors as well.

But another possible answer to the first question is that some of this growth has not in fact been decoupled but come to rely on water from elsewhere. The idea of relying on external sources of water should not be new to students of California water. After all, California has historically received up to 10 percent of its water supply from the Colorado River basin, as well as a few percent from Oregon and a tiny bit from Mexico. (Part of California is in fact within the Colorado River basin; however, this area is the smallest among the seven basin states.) These regional imports, however, have not increased in recent decades (in fact they are included in the water-use metric presented in figure 15.2), meaning that water to sustain California's growth might come from even farther afield.

The water footprint approach offers a possible explanation of this situation by acknowledging that water to sustain Californians and California's growth does not need to arrive in the state in liquid form. Rather than import water through pipes, products that use water can be imported. This has been referred to as *virtual water*, *water services*, and *embedded* or *embodied* water. All these mean roughly the same thing, and are an intrinsic part of California's water footprint. The water footprint method, as we have presented it here, helps identify where and how this water was brought into production for sustaining California. Thus, our assessment aims to offer deeper answers to fundamental sustainability questions about how water has figured in California's past and future development.

With these questions in mind, as well as the tools outlined in the previous section, we now consider what California's water footprint has looked like and what implications it has for future sustainability. The products accounted for in California's water footprint are shown in figure 15.4. Most of California's water footprint, like that of the average Californian, relates to food (85 percent). Meat and dairy products are especially water-intensive, making up half of the food portion. Energy products such as gasoline, ethanol, electricity, and natural gas make up the next-largest piece (8 percent) of California's water footprint, followed by industrial products (3 percent) and direct use of water for domestic, commercial, and institutional purposes (3 percent).

Next we look at how California's water footprint has changed over time. Lack of continuous data limited our results to snapshots at 5-year intervals starting in 1992, which makes for a kind of strobe-light view of the actual evolution of California's water footprint. Nevertheless, figure 15.5 reveals several interesting points. Total water footprint for

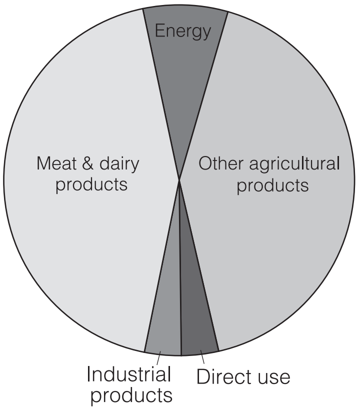

FIGURE 15.4. California's water footprint, by product class.

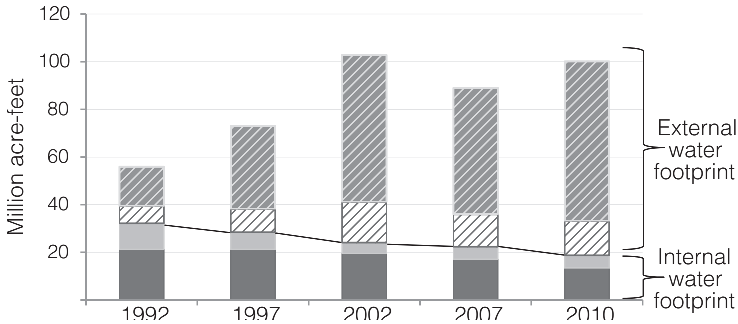

FIGURE 15.5. Evolution of California's blue and green water footprint since 1992. Blue water is represented in dark grey, green water in light grey.

each year is divided between external and internal, as well as blue and green components. In 1992, most of California's water footprint was internal, meaning that it came from the use of California's surface and groundwater. Just over half was also blue water. By 1997, at our next time step, we can see three trends developing that eventually proceed throughout the time series: an increase in the overall volume of the water footprint (overall bar height); increasing reliance on green water (relative size of the light-gray solid and hatched boxes to the total bar); and increasing reliance on external water resources (relative size of hatched boxes to the total bar).

Here we look at each of these trends individually and consider what might be driving it, whether it is policies, economics, environmental constraints, or simply the cumulative lifestyle choices of 38 million (and counting) Californians.

First, consider the trend in total water footprint quantity, as measured by the overall height of the bars. The average water footprint growth rate between 1992 and 2010 was 4.4 percent per year. This is slower than GDP growth (5.2 percent); however, it is more than twice the rate of population growth (1.4 percent). In fact, water footprint per capita has grown at 2.4 percent per year. Why is this? One explanation is that Californians are simply consuming more than in the past. Focusing on food consumption, this trend is somewhat supported by data from the U.S. Department of Agriculture's Food Availability Data System, which shows a 7-percent increase in daily calorie availability for all Americans between 1992 and 2010. These data do not include food losses, which in 2010 were 31 percent of available food (Buzby, Wells, and Bentley 2013). Another explanation could be a change in average per capita diet or consumer behavior toward more water-intensive goods. As shown above, meat consumption can make up a large proportion of an individual's water footprint. A final explanation could be that the amount of water used to make products consumed by Californians is increasing. As noted earlier, production in California has become more water-efficient; however, those efficiency gains will not affect California's water footprint if the water-efficient products are then exported and more water-intensive products imported. A final note on the overall height of the bars is that the spike that shows up in 2002 and then recedes by 2007 is related to the stockpiling of corn grain intended to be used to produce ethanol in subsequent years.

A second observation in California's changing water footprint is the increasing trend in the green water component. As California has very little rainfed agriculture, most of this green water comes from outside of its borders. The growing contribution of green water to California's water footprint raises concerns about the risk of relying on precipitation falling in other regions and the potential impacts of climate change. The 2012 droughts in the U.S. Midwest highlighted this concern when imported grain for livestock and ethanol were in short supply (U.S. Energy Information Administration 2012). This situation provided evidence of California's susceptibility to global climatic changes in regions outside its borders, which are only expected to become more dramatic in coming years. Incidentally, increased dependence on blue water could also expose California to potential impacts of climate change since, ultimately, sources of blue water such as surface water reservoirs, groundwater aquifers, rivers, canals, and streams are also directly dependent on the overall precipitation in an area. Nevertheless, management of blue water offers some flexibility to cope with year-to-year variations in precipitation.

Our third and perhaps most dramatic finding is that California's water footprint has become increasingly externalized, from 40 percent in 1992 to 80 percent in 2010. This means that to sustain itself California now relies far more on water resources from outside its borders than it did in the early 1990s. Most of this water is from other parts of the United States, but the percentage of virtual water from other countries has nearly doubled, from 21 to 41 percent, over this time period. The further externalization of California's water footprint raises concerns about our ability to manage water resource impacts and risks associated with our demand for goods and services. In the next section we look at how these impacts and risks are distributed in more geographic detail. At the same time, California's internal water footprint has decreased from 60 percent to 20 percent of the total, theoretically reducing its burden to water resources inside its borders. However, as shown in figure 15.3, water withdrawals have remained stable in California. Virtual water exports explain this apparent difference. The amount of water embedded in exported products has increased by an average of 6.2 percent per year since 1992.

Fundamental sustainability questions are raised by the relationship between water use and growth in population and GDP (figure 15.3). Summing up these findings, we see clear indications that sustaining California's growth has relied heavily on virtual water. On a per capita basis, virtual water has been used not just to sustain existing consumption habits but to support changing behavior toward higher levels of consumption as well as consumption of more water-intensive products. Most of the virtual water Californians have come to rely on in the past 20 years has been green water, which has quadrupled, although import of virtual blue water has at least doubled. Lastly, the sustained growth of California's water footprint over the past 20 years has been entirely permitted by the increased reliance on virtual water from outside its borders. While water resources actually managed within California have been increasingly applied to exports, a larger and larger share of California's growth has been sustained by water from elsewhere. In the next section we present a geographic analysis of California's water footprint.

To develop an understanding of the impacts and risks related to California's water footprint, the next step is to determine where water is used to sustain California's economy and population. As seen in the

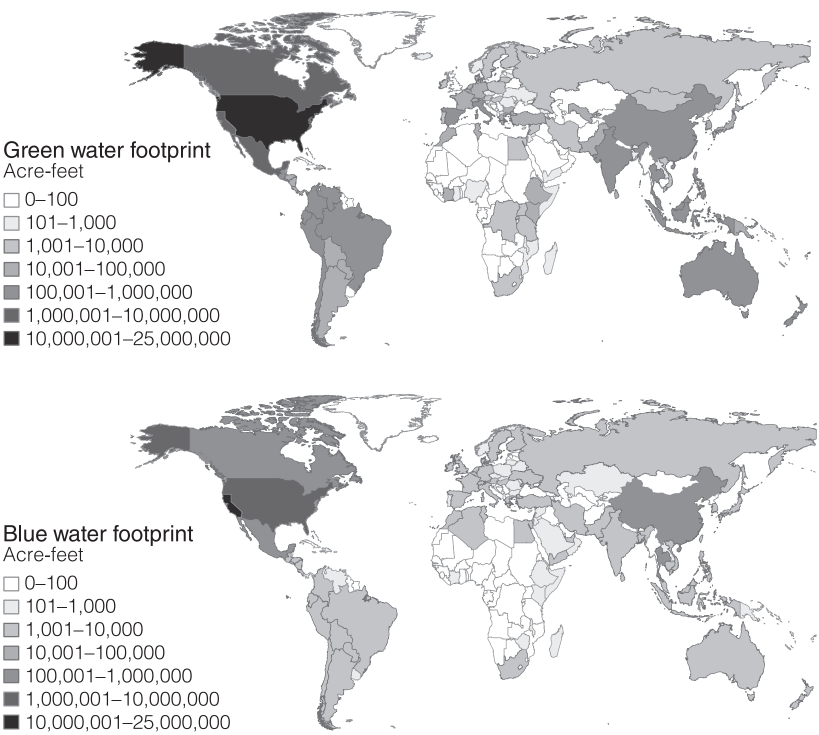

FIGURE 15.6. California's green and blue water footprints, by country.

previous section, 80 percent of that water is outside its borders. Figures 15.6(a) and (b) depict where water is used to make products consumed in California. As can be seen in figure 15.6(a), most of the green water relates to production in other U.S. states, where we have already highlighted some of the risks associated with droughts. Similar risks appear in California's major trading partners, Mexico and Canada, where Californians depend on green water to the tune of several million acre-feet. (An acre-foot is the amount of water that would flood one acre—about the size of a football field—to a depth of one foot.) Further dependence on green water can be noted in drought-prone countries like Australia, parts of India and China, and East African and Mediterranean countries, as well as most of South America.

Figure 15.6(b) shows that California's largest dependence on blue water is within the state itself. Nevertheless, dependencies amounting to several hundred thousand acre-feet exist with neighboring Mexico and Canada, as well as the country providing the most imports to the United States of any trading partner: China. Despite massive investment in China's water infrastructure, there is increasing evidence of a "ruinous confrontation between water supplies and its increasing food and energy demands that is virtually certain to grow more dire over the next decade" (Schneider 2011). China also figures most prominently in California's grey water footprint (not shown) due to the quantity of goods imported from China's industrial sector, often cited as one of the most polluting worldwide.

Though figure 15.6 shows California's water footprint on a map of countries, it is important to understand that water impacts are usually experienced not at the national scale but rather at the scale of river basins. For example, China is a large country with multiple river basins and differing hydrologic conditions. Characterizing the sustainability of California's blue water footprint there would require first knowing in which basins goods were produced that California imports and then understanding the sustainability concerns associated with consuming that volume of blue water. Such techniques are possible but were beyond the scope of this initial assessment.

Concluding this section, we have shown that California's sustainability is intimately tied to water use and impacts in virtually every corner of the earth. The results presented here are a first-order analysis intended to raise awareness of the global nature of water sustainability for California and highlight the general structure and evolution of California's water footprint. We have attempted to take this step in a manner consistent with the intention of water footprint science, but much more analysis and effort are needed to characterize the nature of the connections we have drawn. Given the promise that we see in this scientific frontier, the next section is intended to highlight the major sources of uncertainty and variability in this and future water footprint assessments. We conclude by discussing how water footprint science can support sustainable water management going forward.

WATER FOOTPRINT VARIABILITY AND UNCERTAINTY

Because we advocate for water footprint being used as a scientific tool to assess water sustainability and develop actionable goals, an important consideration is how certain we can be in our calculations. There are several sources of variation in the calculated water footprint for a population (e.g. California). Some of these are related to variation in the behavior that leads to consumption of virtual water; some are related to geographic and other variation in water availability and use in goods production; and some are related to measurement error and accuracy of values used in calculations of virtual water use and impacts.

Agricultural/food production is the largest component of California's water footprint: 85 percent of it in 2007 (Fulton, Cooley, and Gleick 2012). Considering the importance of agricultural water demand in California, we estimated the impact of the variability in the water footprint of agriculture production on the total water footprint for the state. Blue water footprint and green water footprint of agricultural production describe the amount of water consumptively used in the growing of crops. Values for blue water footprints come from estimates of the total volume of evapotranspiration of applied water from agricultural crops, while green water footprints are derived from the total volume of effective precipitation. To assess variability in the water footprint estimates, a range of values for evapotranspiration of applied water and effective precipitation were used from the smallest-scale units used in the analysis. We found that variability in evapotranspiration of applied water among nine major crops resulted in the water footprint of agricultural production ranging by about 30 percent around the mean water footprint across 4 years of analysis. This is a result of a combination of differences in water use for the same crop in different places and at different times. If all other sources of variation are ignored, this variation results in the California water footprint varying by about 13 percent around the mean of 1,500 GPCD. This means that our estimate of the water footprint is pretty good.

Another source of variation in water footprint is in individual choices of consumable goods and services. One factor that seems to be a strong determinant of water footprint of consumption is income, with people who make more money tending to consume more goods and thus have a larger water footprint (Hoekstra and Chapagain 2006). To estimate the impact of variation in income within California on calculated water footprint, we assumed that the influence of national income levels on water footprint was approximately correct when used at finer scales, such as for a county within California. We used income data from the Census Bureau for select counties (Orange, Riverside, and San Bernadino) and the Water Footprint Network's online calculator (www.waterfootprint.org/?page=cal/waterfootprintcalculator_indv) to estimate individual water footprints. There was considerable variation around the mean income values, with 4.5–6.9 percent of households occupying the lowest income category (<$10,000/y) and 2.9–9.4 percent the highest ($200,000/y). This variation in income resulted in a range of calculated water footprints from ~640 GPCD for the poorest households to ~4,200 GPCD for the wealthiest. This indicates that if households in California act similarly to households around the world, then one large source of variation in water footprint will be rates and types of consumption, based on income.

A third factor causing variation in water footprint is diet, with vegetarian and vegan diets having lower water footprints than meat-containing diets (da Silva et al. 2013; Vanham 2013). This is because it takes more water to produce meat than the caloric or weight equivalent of vegetables and grains. Using the Water Footprint Network's online calculator, we found that for a moderate individual income of $30,000/y a vegetarian diet resulted in a 27-percent lower water footprint than a meat-containing diet. There is no similar calculator for a vegan diet, but it is likely that the water footprint for a person with a vegan diet will be considerably lower than for someone with a meat-containing or vegetarian diet.

Measuring uncertainty in water footprint calculations is useful because it helps to build confidence in the footprint as a tool to inform decisions. In our analysis we found uncertainty in much of the data. For example, first calculating the water footprint of products produced within California, we found uncertainty stemming from the production statistics and surveys/models of consumptive water use that were used to derive blue and green water footprint factors. And with respect to virtual water imports and exports, there is a great deal of uncertainty in trade data as far as how products are categorized and how the magnitudes of their trade flows are calculated.

Measuring uncertainty is also useful to find out how much individual and collective water footprint can vary due to environmental and consumption patterns, because these patterns often involve choices. This means that people can decide to change their water footprint by changing their consumption of water-intensive foods and goods. Because a lot of the variation within the water footprints of individual crops is related to where they are grown, this also means that decisions about crop production among subregions (e.g. within California) can include information about water intensity, which provides a role for water managers in improving sustainability of water use.

WATER FOOTPRINT AND MANAGING WATER

A key question is whether or not the water footprint can be used by individuals and water managers in making decisions about water sustainability. Global climatechange will affect regions in different ways and is likely to affect the reliability of receiving imported goods and services. This will in turn affect water management in geographic areas that are importers of these goods, such as California, as domestic sources either make up for shortfalls in imports through increased production, or reduce their water use due to international trade pressures. Calculating and using the water footprint in water planning and assessment is an acknowledgement that we participate both in global trade and in a single water cycle.

One interesting thing about the use of water footprints in water-related decision-making is that it can be done across spatial and organizational scales. Individuals may choose to reduce their consumption patterns or increase their support for broader water management efforts based on improved understanding of the relative sustainability of water used in particular goods and services. Companies can improve their understanding of how components of their supply chain may be at risk from variations in water availability and take actions to minimize those risks. Water managers can improve their understanding of how regional or state-scale water use for goods production may change in response to the swings in water use in globally traded products.

We find that 80 percent of California's water footprint is associated with products made outside the state's borders, including other U.S. states and other countries. This is dramatically different from 20 years ago, when California's water footprint related mostly to products made inside California. This means that California is becoming increasingly dependent upon goods from other states and countries and therefore dependent upon and vulnerable to water availability and management in those regions. Over the next century, virtually all of California's current trading partners will have from mild to severe water stress, suggesting risk to California's supply chain from global and U.S. sources.

Agricultural production is the largest component of an individual's or region's water footprint. Coupling virtual water with economic information describing the production value of a crop can strengthen agricultural water management. Spain was the first country in the European Union to include water footprint analysis in its river basin management plan (in 2009). The analysis included questions on when and where water footprints exceed water availability, how much of a catchment's total water footprint is used in producing exports, and the volume and value of crops produced per unit of water (Hoekstra and Mekonnen 2012). "Water economic productivity," expressed in terms of crop market value per cubic meter of water used, has been derived, for example, for the Mancha Occidental region of Spain (Aldaya, Martínez-Santos, and Llamas 2009). That study distinguished "low virtual water, high economic value" crops from "high virtual water, low economic value" alternatives, in a semi-arid region characterized by irrigated agriculture. The study found that "high virtual water, low economic value" crops, such as cereals, are widespread in the region, in part due to the legacy of subsidies. An expansion of low-water-consumption and high-economic-value crops such as grapevines was identified as a potentially important measure for more efficient allocation of water resources. The study concluded that to achieve significant water savings and environmental sustainability, potentially difficult decisions will have to be made regarding crop choice and water allocation. Pricing and regulation of allocation could be used as complementary mechanisms to allocate water to those crops that generate the highest economic value at low water demand.

One of the most promising advances in using water footprint assessments to measure sustainability is the increasingly fine scale at which calculations can be made, which increases the range of uses and users of this index. For example, people can choose food and other consumables based on the calculated and reported water footprints of these items. Just as importantly, producers and regional trade groups can use the total size and intentional improvements (reductions) in water footprints of their products to improve their competitive status with informed consumers. Because of the amount of fine-scale water and economic data available and the prevalence and familiarity of online tools, both users and producers can estimate the water footprint of products and act in concert to improve overall water sustainability.

CONCLUSION

Thinking back to the cup of coffee that started the chapter, what else do you understand about it after reading this chapter? Hopefully you think there is more than just a cup of coffee, possibly even revealing a new way to consider water sustainability for places like California. First we said that a thousand times as much water was used to bring that coffee to you, and that millions of times as much is needed to provide everything else you use and consume in a year. Second, we tried to convince you that you should care about that water because your sustenance, your family's and neighbors' sustenance, and California's sustainability are all wrapped up in the story of that water and how it touches other places and people. Third, we walked through how water footprint science tries to tell that story in a consistent framework that gets at the impacts and risks associated with interventions in the hydrologic cycle to produce the products we depend on. Fourth, we described how we used that science to understand, in macro terms, California's evolving story with water inside its borders as well as in other places, outside of its borders. Fifth, we qualified those understandings with a discussion of uncertainty in water footprint science and how it can be improved. Lastly, we highlighted possible applications of water footprint science and information to various levels of decision-making among individuals, companies, and government agencies. Water footprint assessments and their application to policy are finding firmer footing around the world and in various sectors. California is a place where sustainability science has had a profound impact on political action and social organization. Water footprint science can help build on these achievements and continue to make California and Californians leaders in water sustainability into the twenty-first century.

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