

CHAPTER 12

Sustaining Water Resources



Paolo D'Odorico and Ignacio Rodriguez-Iturbe

*“As the rain and the snow
come down from heaven,
and do not return to it
without watering the earth
and making it bud and flourish, ...”*

(Isaiah 55:10)

Summary Life depends on water and there are no substitutes. Fundamental to the functioning of the Earth's system, water is a renewable natural resource that is available in finite amounts. Human appropriation of freshwater resources is mainly used for agriculture. To prevent loss of natural habitat and biodiversity, the growing demand for agricultural products will likely need to be met by enhancing crop yields in currently cultivated land rather than through farmland expansion. Because of local limitations in water availability, irrigation can be sustainably expanded only in part by the currently rain-fed farmland. Any further withdrawal from water bodies would deplete environmental flows or groundwater stocks. Local water deficits (i.e., gaps between availability and demand, including water for food) are often compensated for by food imports from water-rich regions and the associated transfers of “virtual water.” Thus, water is a strategic resource that has become strongly globalized and controlled by a few countries, while the rest of the world is in conditions of trade dependency. Water-saving strategies—based on food waste reduction, moderation of diets, use of more suitable crops, or increased water use efficiency—need to be adopted in order to meet human needs without compromising water sustainability.

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Background

Water is essential for life on Earth and plays a crucial role in determining the global distribution of biomes as well as habitats for aquatic and terrestrial species (e.g., Whittaker, 1975). It also shapes the land surface through erosion and deposition processes; transports sediments, nutrients, and pollutants; and drives the dispersal of a number of species and pathogens (e.g., Dunne & Leopold, 1978). Water is also an important determinant of the Earth's climate because of heat storage in water bodies, the impact of evaporation and transpiration on the surface energy balance, and the effect of water vapor on atmospheric radiative transfer. Water availability affects the productivity of terrestrial ecosystems, the rate of global biogeochemical cycles, and the composition of plant, microbial, and animal communities (e.g., Rodriguez-Iturbe & Porporato, 2005). The impact of water resources on human societies is evidenced by the critical role of water in a number of human activities, such as agriculture, manufacturing, energy generation, and mining.

The majority of terrestrial ecosystems and most human activities rely on freshwater, which accounts for about 3% of the global water resources (with the remaining 97% being in the oceans). Most of the freshwater on Earth is in ice caps ($\approx 69\%$) and groundwater ($\approx 30\%$), while only about 1% is stored in surface water bodies and vegetation.

Atmospheric water reaches the land surface as precipitation and then either flows downhill as surface runoff or infiltrates into the ground, thereby contributing to root zone soil moisture and groundwater recharge (Fig. 12.1). Water retained by capillary

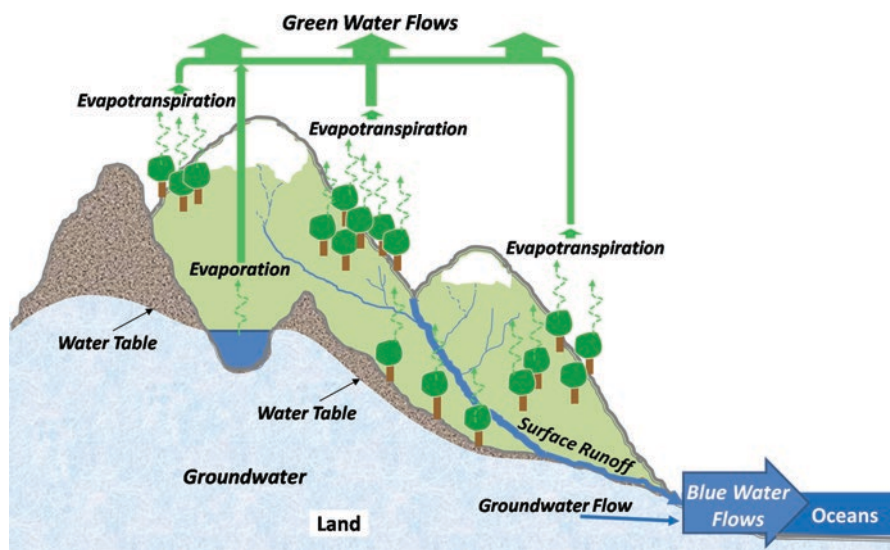


Fig. 12.1 Blue water flows (i.e., runoff) and green water flows (i.e., evapotranspiration) out of land masses

forces in shallow unsaturated soils is often termed “green water” because it is largely used by plants and soil microorganisms that can exert the suction required for extraction. The majority of terrestrial plants relies on green water. Conversely, groundwater (i.e., in the saturated portion of below-ground water stocks) and surface water are often referred to as “blue water” (Falkenmark & Rockström, 2004).

Water leaves land masses either in the liquid phase as blue water flows, or as water vapor fluxes associated with evapotranspiration (i.e., green water flows) (Fig. 12.2). Globally, blue water flows account for about 40% and green water flows for 60% of the water fluxes from land masses. These proportions, however, vary across geographic regions and have been altered by human action.

The two major anthropogenic disturbances to the water cycle are associated with land use change and irrigation. These phenomena have opposite effects on hydrological processes. Land use change—typically in the form of deforestation and land conversion to agriculture—tends to reduce evapotranspiration and increase runoff (e.g., Bonan, 2008). In other words, it reduces green water flows and increases blue water flows. Conversely, irrigation, which accounts for the majority ($\approx 70\%$) of water withdrawals for human activities, uses blue water from streams, lakes, and aquifers to enhance agricultural yields by increasing crop evapotranspiration (i.e., turning blue water into green water flows). In many regions of the world, the latter effect is predominant and explains the observed reduction in river flows in major agricultural regions. Indeed, some rivers (e.g., the Rio Grande, Colorado, Nile, and Yellow Rivers) are so strongly depleted that they do not reach the ocean anymore. Particularly emblematic are the cases of endorheic basins, such as Lake Chad, The Dead Sea, The Aral Sea, and Lake Urmia, which are drying out because of water withdrawals from their tributaries (e.g., Stone, 2015). Likewise, many aquifers around the world are strongly depleted because withdrawals (often for irrigation or municipal uses)

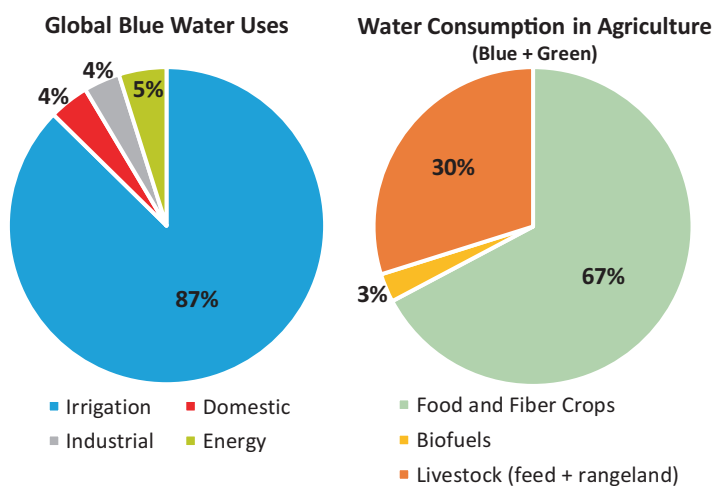


Fig. 12.2 Global blue water consumption (left) and total (blue and green) water consumed in agriculture (data from Table 12.1 for years around 2000)

are occurring at rates exceeding those of groundwater recharge, a phenomenon often known as “overpumping” (Konikow, 2011; Wada et al., 2010). Moreover, agriculture may affect the water cycle through the impacts of irrigation and land use change on precipitation, evapotranspiration and runoff (e.g., Bonan, 2008).

Changes in the water cycle are also emerging as a result of climate warming, which causes a slight intensification of the water cycle with a 2–3% increase both in global precipitation and evapotranspiration per Celsius degree of global temperature increase. These global averages, however, do not show how local precipitation is expected to either substantially decrease or increase depending on the location. As a general pattern, humid regions (e.g., at the equator and midlatitudes) are expected to become wetter, while drier regions (e.g., the subtropics) drier (Held & Soden, 2006). The impact on crop production, however, should also account for the effect of increased atmospheric CO₂ on photosynthesis and the nutritional properties of crops (Myers et al., 2014).

Thus, water is a renewable resource that is conserved within the earth system. Some water stocks (e.g., glaciers, aquifers, and endorheic lakes), however, are undergoing depletion. Likewise, in some areas, water quality is degraded by pollution from chemicals, suspended sediments, and pathogens. Despite its renewability, water is available on Earth only in limited amounts. Therefore, some human activities are constrained by the pace of the water cycle, and competition often exists between human uses and environmental needs.

Human Appropriation of Water Resources

Human societies use “blue” water resources for agriculture, industrial, energy, and household needs. The majority of these uses are related to crop production, in the form of irrigation water (Fig. 12.2). Therefore, contrary to common perception, the global water crisis is all about finding solutions to mitigate and prevent hunger rather than thirst (e.g., Falkenmark & Rockström, 2004). Thus, problems of water scarcity are closely related to important constraints on food production. While economic access is often recognized as the main cause for undernutrition, limited availability in periods of drought is typically the driver overlying spikes in food prices and associated food crises. Insufficient caloric intake may cause acute malnutrition (weight loss and/or inability to gain weight), a major cause for child mortality. Insufficient protein intake in the first 1000 days in the life of a child can cause chronic malnutrition (i.e., stunting) with permanent physical and cognitive impairment in children. Overall, malnutrition affects about 800–900 million people worldwide. Even though protein-rich food products tend to require three to six times more water per calorie than plant food, this chapter shows how the water needed to eradicate undernutrition can be sustainably met by the global water resources of the planet.

In this context, there is a difference between water withdrawals from water bodies and water consumption (i.e., evapotranspiration) by agriculture. Only a fraction of the water that is withdrawn from water bodies and applied to cropland is actually

evapotranspired. The difference between the two eventually contributes to return flow to nearby water bodies and is available downstream for human uses or environmental need. Conversely, the water lost through evapotranspiration (or “consumptive use”) will become available again after precipitation at a rate determined by the pace of the water cycle.

The energy sector is also a major water consumer, though at much smaller rates than that of agriculture. Almost all forms of energy production require water, both for the extraction of energy resources and for power generation. It has been estimated that energy production (2014 data) accounts for 400 km³/year of blue water withdrawals and 50 km³/year of consumptive use (IEA, 2016). These estimates include blue water for primary energy source extraction and power generation (Table 12.1) but do not include green water consumption for energy production from biomass (e.g., wood, bioethanol, and biodiesel) and losses from reservoirs for hydropower generation. The total water consumption for biofuel production is roughly 200 km³/year (Rulli, Bellomi, Cazzoli, Carolis, & D’Odorico, 2016), which is about 2.4% of the water use in agriculture (Table 12.1).

Environmental Impacts of Water Withdrawals

The impacts of overpumping differ depending on whether it affects aquifers or surface water bodies. Many regions of the world, including the North-American Southwest, Northern Africa, the Indo-Gangetic Plain, the North China Plain, and the Arabian Peninsula, are affected by groundwater depletion (Konikow, 2011). Globally, groundwater depletion accounts for 20–33% of global groundwater withdrawals (Table 12.1).

The case of overuse of surface water resources is different because it raises concerns about the loss of aquatic habitat. Indeed, freshwater ecosystems exhibit high levels of biodiversity but are susceptible to much greater extinction rates (about five times) than those of other terrestrial ecosystems (Postel & Richter, 2003). To maintain biodiverse freshwater ecosystems, we need to ensure that suitable minimum flow and water quality requirements are met and that the timing, frequency, and magnitude of both high and low flows are not disrupted. Ecologists have defined minimum flow requirements (or “environmental flows”) to place a cap on sustainable water use (e.g., Pastor, Ludwig, Biemans, Hoff, & Kabat, 2014; Richter, Davis, Apse, & Konrad, 2012).

Water Use for Agriculture

Most of the agricultural production on Earth is rain-fed and does not rely on irrigation. Roughly 18% of the global cultivated land is presently irrigated (Fig. 12.3) and contributes to about 40% of global agricultural production (e.g., Rosa et al., 2018).

Table 12.1 Global water flows and demands in km³/year

	Annual flow (km ³ year ⁻¹)	Year	Source
Precipitation over land	120,000		Chow (1988)
– Evapotranspiration from land (green water flows)	72,000		
– Global runoff (blue water flows)	48,000		
Planetary boundaries of blue water	4000		Rockström et al. (2009)
Water withdrawal for irrigation	2560	2000	Sacks et al. (2009)
Water consumption for irrigation	1280	2000	Siebert and Döll (2010)
	899	1996–2005	Mekonnen and Hoekstra (2011)
Unsustainable water consumption from irrigation	336	2000	Rosa et al. (2018)
Groundwater consumption for irrigation	540	2000–2010	Siebert and Döll (2010)
Groundwater withdrawals	730	2000	Wada et al. (2010)
Groundwater depletion	140	2001–2008	Konikow (2011)
	200	2000	Wada et al. (2010)
Water consumption for crop production (green + blue water)	6670	1996–2005	Mekonnen and Hoekstra (2011)
	11,800	2010	Carr et al. (2013)
Green water consumption for food production	5771	1996–2005	Mekonnen and Hoekstra (2011)
	6150	2000	Rosa et al. (2018)
Water consumption in rangelands and pastures	910	1996–2005	Mekonnen and Hoekstra (2011)
Water for livestock production (blue and green)	2260	1996–2005	Hoekstra and Mekonnen (2012)
Freshwater used for biofuel production	220	2013	Rulli et al. (2016)
– Green water for biofuel crops	170		
– Blue water for biofuel crops	11		
Virtual water trade (food only)	2810	2010	Carr et al. (2013)
Water grabbing	450	2013	Rulli et al. (2013)
Freshwater withdrawals for energy production	400		
– Primary energy source extraction	50	2016	IEA (2016)
– Power generation	350		
Freshwater consumption for energy production	50		
– Primary energy source extraction	34	2016	IEA (2016)
– Power generation	16		
Freshwater withdrawals from domestic sector	400–450	2000–2010	Wada et al. (2016)
Freshwater consumption from domestic sector	42	1996–2005	Hoekstra and Mekonnen (2012)

“Year” denotes the period considered in each study (see also D’Odorico et al., 2018)

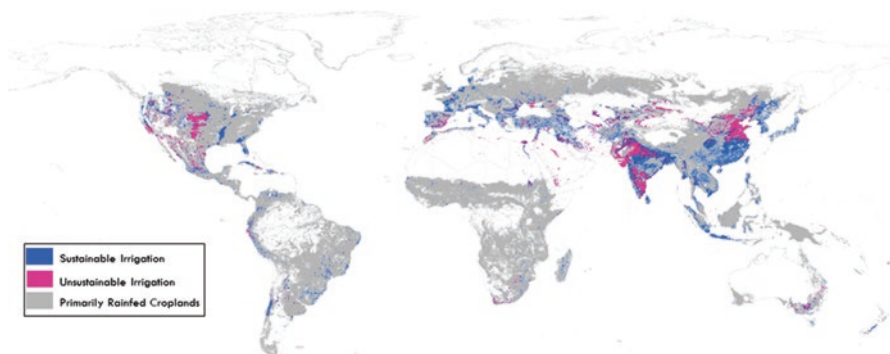


Fig. 12.3 Current irrigated land. Areas with less than 5% irrigation (based on data by Siebert, Henrich, Frenken, & Burke, 2013) and where more than 90% of crop water needs are met by rain-fed agriculture have been masked. According to these criteria, irrigated areas account for 2.5×10^6 km², which is about 18% of the global cultivated land. (Based on Rosa et al., 2018)

Rain-fed agriculture relies only on green water resources, while irrigated agriculture uses both green and blue water.

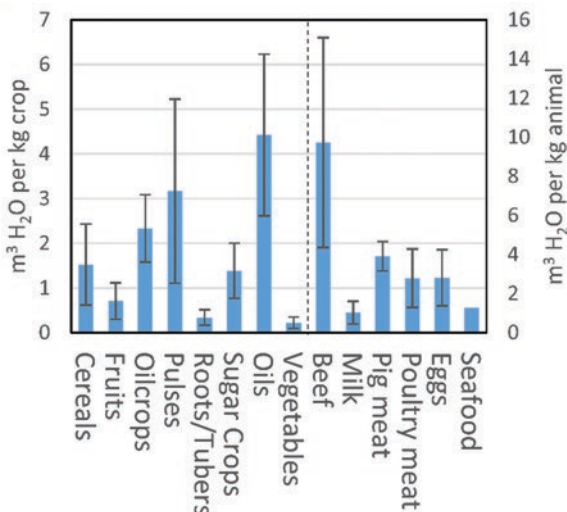
Green water is often taken for granted because it is directly acquired with the land without requiring investments in infrastructure for its capture or institutional arrangements to define the right to use it. The choice to plant certain crops may strongly affect evapotranspiration losses, with an indirect impact also on runoff. These effects of agriculture on croplands' hydrologic response are often ignored.

Sustainable and Unsustainable Water Use for Irrigation

Estimates of global water consumption for irrigation (Table 12.1) vary between 900 and 1280 km³/year (Mekonnen & Hoekstra, 2012; Siebert & Döll, 2010), while withdrawals range between 2410 (Jägermeyr, Pastor, Biemans, & Gerten, 2017) and 2560 km³/year (Sacks et al., 2009). Even though these values are well within the sustainability limits (or “planetary boundaries”) identified by some authors (≈ 1100 –4500 km³/year, Gerten et al., 2013; Rockström et al., 2009) and are way below the global estimates of blue water flows (4800 km³/year, see Table 12.1), there are numerous instances of locally unsustainable water uses.

As a major form of human appropriation of blue water resources, agriculture is the main reason why environmental flows have been strongly depleted in many rivers worldwide. About 41% of water withdrawals for irrigation (Jägermeyr et al., 2017) and 40% of irrigation water consumption (Rosa et al., 2018) are unsustainable because they occur at the expenses of environmental flows and/or groundwater stocks (Fig. 12.3).

Fig. 12.4 The water footprint of major crops and animal products (based on data in Davis et al., 2016)



Livestock Production

About 30% of agricultural water consumption is used for livestock production, mostly (>90%) in the form of green water for feed, fodder, and rangeland grazing (Table 12.1). It takes much more water to produce a calorie of food from animal products than from crops. The consumption of meat-rich diets remains a water-intensive (and carbon-intensive) lifestyle (e.g., Davis et al., 2016; Tilman, Balzer, Hill, & Befort, 2011). Thus, the observed trend of decreasing cereal consumption and increasing reliance on animal products with increasing levels of affluence (Tilman et al., 2011) is expected to enhance the human pressure on global freshwater resources (e.g., Davis et al., 2016). Are these hydrologic effects of dietary changes on water consumption of the same order of magnitude as those of demographic growth? Using a GDP-based projection of dietary change, Davis et al. (2016) estimated that by 2050 the average per capita water consumption for food production will increase by 19% from the present level, while population growth is expected to increase by 35%, reaching 9.8 billion people by 2050. Thus, the hydrologic impact of dietary shifts in the burgeoning developing societies is expected to be of the same order of magnitude as demographic growth (Fig. 12.4).

Projections of Future Water Needs for Food Production

To meet the food needs of the increasing global population while eradicating undernourishment, humanity will likely need to reduce food waste and the consumption of resource-intensive products (e.g., Foley et al., 2011). In fact, there are limits to

the sustainable increase in food production, and some of these limits are associated with water resources (Falkenmark & Rockström, 2004).

Recent studies have stressed the danger of increasing food production by expanding agriculture because it would result in habitat destruction, biodiversity loss and CO₂ emissions. Therefore, scientists have been advocating for the intensification of agriculture in land that is presently cultivated (or “land sparing”) (Foley et al., 2011). Intensification typically requires the use of fertilizers, irrigation, and other modern technology to close the yield gap, which is the difference between actual and maximum potential yields. Yield gap estimates are typically developed without evaluating to what extent the local hydrologic conditions allow for a sustainable development of irrigation. Indeed, large tracts of agricultural land are not suitable for sustainable irrigation, while in 26% of currently rain-fed areas it is possible to irrigate without depleting environmental flows or groundwater stocks (Rosa et al., 2018). If at the same time current unsustainable irrigation practices (Fig. 12.3) were eliminated, sustainable irrigation expansion would allow for a 24% increase in global food production that could feed an additional 1.8 billion people (Rosa et al., 2018). Collectively, these results demonstrate the existence of limits to the sustainable appropriation of water resources for agriculture and to humanity’s ability to sustainably increase food production. Further needs for water resources for food production will need to result from water conservation (D’Odorico et al., 2018).

Pathways to Water Conservation

A more sustainable approach to water and food security looks at a reduction of consumption as an alternative to increasing production. The ongoing pattern of overconsumption can be broken by reducing food waste, promoting the shift to diets that are less resource intensive, and decreasing the amount of food intake in over-nourished populations.

Waste Reduction

About 24% of the water used for food production is lost through food waste (Kummu et al., 2012). These losses occur at different stages along the “farm to fork” supply chain, depending on the type of food, access to refrigeration and transportation facilities, and household habits. In the last few years, there has been a push toward a circular economy of food to reduce resource consumption and waste accumulation by repurposing and reusing food products (e.g., Stahel, 2016). In some countries, the destruction of unsold food by retailers or distributors is avoided through timely donations to food charities. Some food types can be reused to produce other food

commodities, or utilized as feed, compost or substrate for biogas production. Likewise, nutrient-rich wastewater can be reused for irrigation, biogas production, or to recover critical nutrients such as phosphorus (Cordell, Drangert, & White, 2009).

Changes in Diets

A reduction in human demand for water resources could result from a switch to less meat-intensive diets. For instance, the shift to vegetarian or pescatarian diets would save 18–21% of the water used for food production and improve human health (Davis et al., 2016; Tilman & Clark, 2014). Human diets are the result of historical habits and cultural heritages and are therefore hard to change (e.g., Wellesley, Happer, & Froggatt, 2015). A positive sign can be seen in the ongoing *livestock transition*, the replacement of resource-intensive bovine meat with pork and poultry (Davis et al., 2016; Thornton, 2010).

Crop Water Management

While transpiration is a productive water loss from terrestrial ecosystems, evaporation does not contribute to plant growth and can even negatively affect soil properties by increasing salinity. Therefore, to produce more food with less water, agricultural practices need to reduce evaporation and maximize transpiration (Falkenmark & Rockström, 2004). Improvement in water productivity based on soil water management could reduce current water withdrawals for irrigation by about 1200 km³/year (Jägermeyr et al., 2016).

Improving Crop Suitability by Replacing Crops

Improvements in water use efficiency to produce “more crop per drop” can be attained either by using new cultivars or by changing crop distribution. The current distribution of crops often makes a suboptimal use of water resources. Water-demanding crops are often planted in arid and semiarid regions. Perennial plants are often cultivated in climates affected by episodic droughts that could kill what took years to grow. Alternative crop distributions can maximize production and feed about 825 million additional people, while saving 12% of irrigation water without sacrificing crop diversity, nutritional value, or land (Davis, Rulli, Seveso, & D'Odorico, 2017). This approach does not require major investments in modern technology that small-scale subsistence farmers in the developing world might not be able to afford.

Water Savings through Trade

Another option to save water is through trade, that is, by producing crops in more suitable areas and exporting them to other regions of the world. Indeed, the current patterns of trade contribute to water savings for about 350 km³/year (Hoekstra & Chapagain, 2008). Other studies found smaller savings and documented their growth over time, from roughly 50 km³/year in 1986 to 240 km³/year in 2008 (Dalin, Konar, Hanasaki, Rinaldo, & Rodríguez-Iturbe, 2012). Further savings could be attained by reshaping trade patterns and future trade intensification.

Globalization of Water

When the withdrawal and consumption of freshwater resources are examined at the global scale, human uses are dwarfed by the magnitude of global runoff and no major environmental impact would seem to emerge from human action (Table 12.1). At a local scale, however, water resources can be strongly stressed by agricultural, municipal, and industrial uses. Several regions of the world are in a state of chronic water deficit because their population by far exceeds the number of people the local land and water resources are able to feed. The existence of countries that are strongly water and food deficient appears to be paradoxical, as one would expect that these conditions would trigger mass emigrations, social unrest, and conflict over the scarce water resources. However, in general this is not the case because trade allows societies to indirectly rely on water resources existing in other regions of the world (Allan, 1998). In other words, the trade of food commodities is associated with a virtual transfer of the water resources required for the production of those goods. Known as “virtual water trade,” this mechanism contributes to the globalization of water resources.

The international trade of virtual water accounts for about 25% of water use in agriculture, including both green and blue water (Mekonnen & Hoekstra, 2012). Thus, while 10–16% of the evapotranspiration by the terrestrial biosphere is contributed by agroecosystems, roughly one-fourth of it is virtually traded (Table 12.1). In the last two decades and a half, virtual water trade has more than doubled in volume and the trade network has become more interconnected. Net exports are mostly contributed by a handful of countries, such as Brazil, the USA, Argentina, Thailand, Canada and Australia (Carr, D’Odorico, Laio, & Ridolfi, 2013). These results suggest that water is a strategic resource that is strongly globalized and controlled by few countries, while the rest of the world is in conditions of trade dependency.

Water is also globalized through transnational land investments, a phenomenon that has intensified over the last decade and a half. Since 2002, about half a million square kilometers of land (i.e., 1.7 times the area of Italy) have been acquired for agriculture and forestry (The Land Matrix, 2017). Land investors can be domestic, foreign, or mixed domestic-foreign ventures that operate as private agribusiness

corporations, government-owned companies, or retirement funds (Cotula, 2013). Investors often target both the land and the water that comes with it. Thus, land acquisitions often become opportunities to secure access to both land and water resources abroad (Dell'Angelo, Rulli, & D'Odorico, 2018; Rulli, Savori, & D'Odorico, 2013). "Water grabbing" is defined as the appropriation of water resources by powerful investors at the expenses of local communities (Dell'Angelo et al., 2018). Appropriation mechanisms may include the redefinition or reallocation of water rights, river diversions, dam constructions, and virtual appropriation of water resources through land acquisitions (Mehta, Veldwisch, & Franco, 2012; Rulli et al., 2013). Interestingly, this phenomenon exceeds the rate of water grabbing from future generations through groundwater depletion (Table 12.1).

Conclusion

Freshwater is crucial to sustain ecological function, food security, energy production, and investments in a variety of businesses. With challenges to water sustainability emerging from growing societal pressures, humanity is facing the trilemma of allocating water to food, energy, or environmental needs (D'Odorico et al., 2018).

How did we reach this point? There have been some major revolutions in the food–water system. The industrial revolution brought about new sources of energy and power, which allowed for the withdrawal and transport of unprecedented amounts of water from surface water bodies and aquifers and the expansion of irrigation to areas not suitable for gravity-driven distribution systems. The green revolution in the decades following World War II led to a major growth in agricultural production with an incredible increase in crop yields. The early phases of the green revolution hinged on the invention of nitrogen fertilizers (e.g., Erisman, Sutton, Galloway, Klimont, & Winiwarter, 2008). At that point, water remained a major limiting factor for crop production, which led to a renewed interest in irrigation infrastructure and improvements in irrigation efficiency.

More recently, the water and food system have been transformed by a "trade revolution." The intensification of trade has allowed some populations to rely on water resources existing elsewhere (Allan, 1998).

A "fourth food revolution" (D'Odorico et al., 2018) is associated with large-scale land acquisitions, a phenomenon that has rapidly accelerated in the last few years, likely in response to recent food crises (Cotula, 2013; Rulli et al., 2013). After some trade-dependent countries experienced conditions of food insufficiency, several agribusiness corporations started to look at regions of the developing world where yields are low because of the lack of investments in modern agricultural technology. This phenomenon contributes to the transition from subsistence or small-scale farming to large-scale commercial agriculture and is often associated with large-scale investments in agricultural land.

All these "revolutions" led to major changes in agriculture, through industrialization, new technology, globalization, and transition in farming systems. With

these changes, humanity has been trying to meet the increasing needs of human societies by sustaining ongoing growth trends in agriculture. Sadly, these changes are frequently accompanied by unsustainable practices and acute social injustices working against the poorest part of the populations. There is the need for new approaches that focus on a reduction in consumption. The pathways to water saving reviewed in this chapter could substantially reduce human consumption of water resources.

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