Global Stressors *on* Water Quality *and* Quantity

Growing population and wealth will impact sustainability, technology selection, and governance strategies related to water issues.

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For more than a decade, the scientific community as well as nongovernmental organizations have sought to raise an alarm concerning the unsustainable use of the planet's available water resources (*1*). Rising world populations and consumption are inexorably increasing human demand for domestic, industrial, and agricultural water. Population and wealth along with other global stressors will have a direct and significant impact on the sustainability goals, technology selection, and governance strategies that are related to water quality and quantity.

On a global basis, ~70% of freshwater is currently used for crop irrigation, ~20% for industrial purposes, and ~10% for domestic purposes (*2*). However, water use varies dramatically from one part of the world to another. Egypt, for example, uses 98% of its water for irrigation, leaving only ~27 L/capita-day for domestic use. In contrast, the U.S. uses 40% of its water for irrigation, and domestic water use exceeds 410 L/capita-day. In refugee camps in Africa and Asia, residents may receive only 15 L/capita-day for both consumption and hygiene. For comparison, the World Health Organization defines reasonable access as the availability of at least 20 L/capita-day from a source within 1 km of the user's dwelling (*3*).

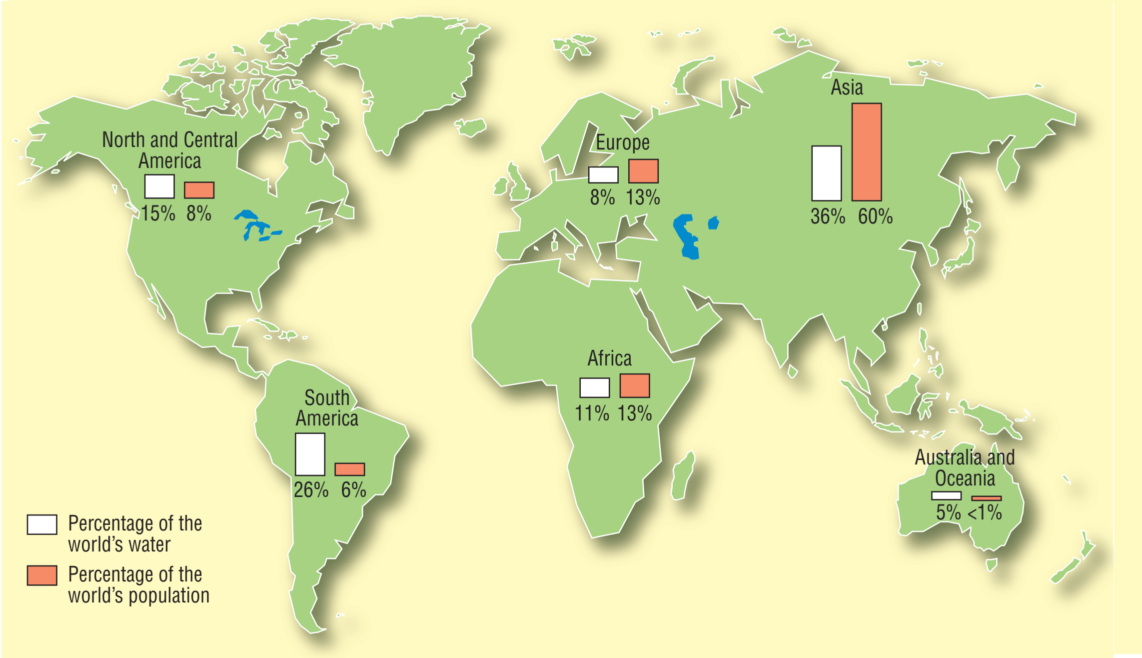
Although the quantity of water used varies by region, water is not distributed equally (Figure 1). This inequality is especially critical for Asia, which has 60% of the world's population but only 36% of the world's water. Water quality in terms of pollutant loading also is not distributed equally and is related to the type of use and a country's level of development (Figure 2). Developing countries often have less capacity to improve water quality and depend on lower-quality water for a variety of uses, including drinking water.

To capture an overall picture of a nation's water use, researchers calculate the national water footprint; this represents the total volume of freshwater used to produce the goods and services consumed by a population and the impact of globalization by

FIGURE 1

Water for people

Global overview of water availability vs population (data from Ref. 4).

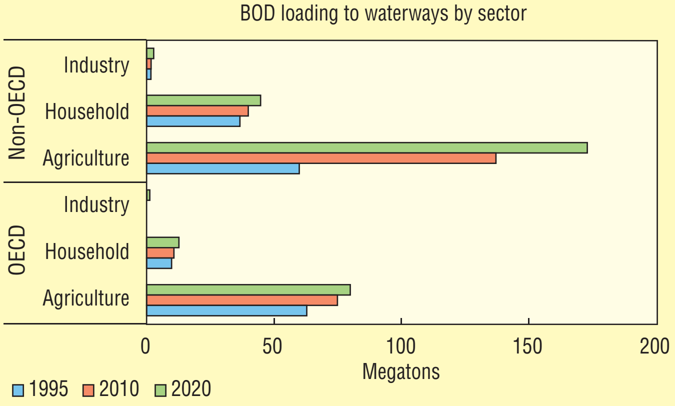


accounting for water across the life cycle of imports and exports (*5*). Water use is measured in terms of water volumes consumed (evaporated) or polluted per unit of time. In this way, it is similar to the concept of "virtual" water, because it accounts for water use associated with consuming agricultural and industrial imports. For the period of 1997–2001, the global water footprint was 1243 m^3/capita-year, 16% of which was the external water footprint (associated with importing goods and services for consumption; *5*). However, some countries have external footprints that account for 50–80% of their total footprint, whereas other countries—for example, some countries in Africa—have external footprints near zero (Figure 3).

FIGURE 2

Water quality

Annual biochemical oxygen demand (BOD) loading in global waterways by sector as an indicator for water quality for 1995 and estimated for 2010 and 2020. The data are compared for Organisation for Economic Co-operation and Development (OECD) countries and non-OECD countries (*4*).



Given the current state of global water interdependence, water will become even more critical and difficult to manage under highly variable future scenarios that involve numerous interconnected global stressors. In this article, we examine the individual and integrated effects of several important stressors on the global water resource: population and consumption, demographic and land-use changes, urbanization, and of course climate change, all of which can contribute to changes in quality, quantity, and availability of water (*7*). We then explore the relationships between these stressors and the design, development, and implementation of technology and governance strategies for sustainable water systems in a dynamic world.

Water stressors

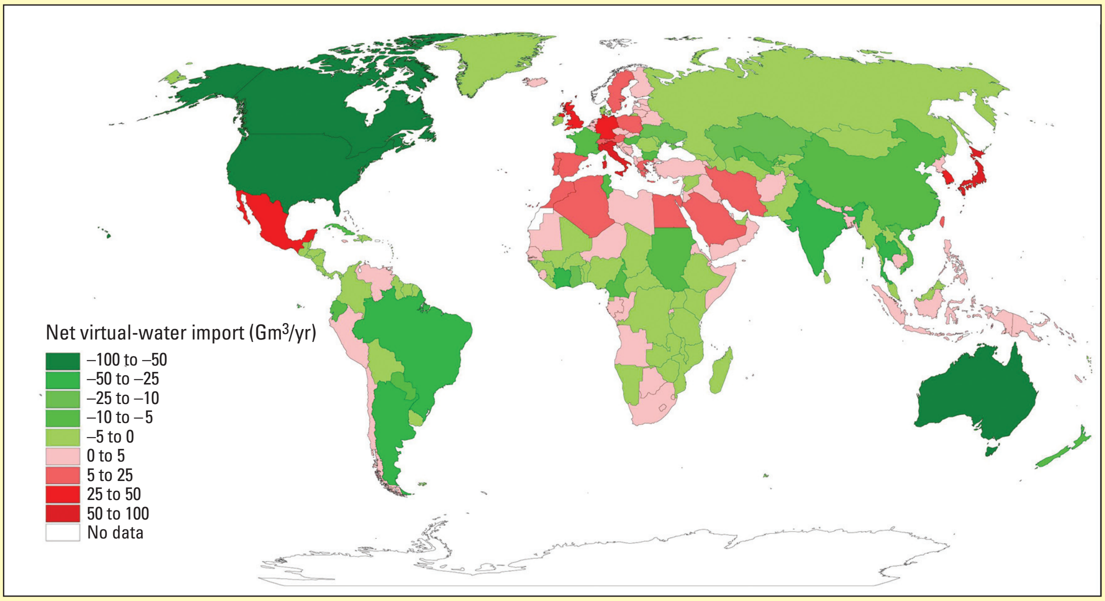
Increased stresses on the world's water are affecting quality, quantity, and availability. Many studies have predicted that climate change will affect water supply and use (*8–10*). Water scarcity felt by 20% of the 1 billion people who are estimated to experience shortages by 2025 is projected to be the direct effect of climate change (*11*). The Intergovernmental Panel on Climate Change has summarized impacts on water resources that are expected by the mid to late 21st century (Table 1; *12*).

According to the best estimates associated with climate change, 75% of the earth's land area will experience increases in runoff compared with 1995

FIGURE 3

Water for trade

National virtual-water balances related to the international trade of products for 1997–2001. Net exporters are shown in green, and net importers are shown in red (*6*).



levels, and 25% will experience decreases (*8*). Higher variability in precipitation and runoff impacts erosion and sedimentation. This particular impact of climate will be exacerbated by changes in land use that result in sedimentation associated with loss of forested riparian cover along streams, filling of wetlands, and agricultural practices. The coastal–urban interface is especially vulnerable to the impact of these integrated stressors because the average population density in these fragile areas is twice the global average. These examples demonstrate the complex and unresolved links between individual stressors. Although the environmental and human response to integrated stressors is still largely unknown, the best strategy to achieve sustainable water systems is likely one that considers the stressors as a system with positive and negative feedback loops, synergies, and interferences.

Figure 4 depicts trends from 1750 to 2000 of some major stressors on water quality and quantity. We note the common shape to all these stressors and resulting impacts—it mirrors the shape of a hockey stick. Stressors are depicted in Figures 4a–4f. Two resulting changes that are occurring globally are also illustrated: the use of water (Figure 4g) and the deterioration of water quality as indicated by nitrogen loading (Figure 4h). Fig-

TABLE 1

Possible impacts of climate change on water resources projected for the mid to late 21st century[1]

Phenomena and direction of trends	Likelihood of future trends[2]	Major impact(s)
Over most land areas, warmer and fewer cold days and nights as well as warmer and more frequent hot days and nights	Virtually certain	Effects on water resources that rely on snowmelt; effects on some water supplies
Warm spells/heat waves; frequency increases over most land areas	Very likely	Increased water demand; water-quality problems (e.g., algal blooms)
Heavy precipitation events; frequency increases over most areas	Very likely	Adverse effects on quality of surface water and groundwater; contamination of water supply; water scarcity may be relieved
Area affected by drought increases	Likely	More widespread water stress
Intense tropical cyclone activity increases	Likely	Power outages causing disruption of public water supply
Increased incidence of extreme high sea level (excludes tsunamis)	Likely	Decreased freshwater availability due to saltwater intrusion

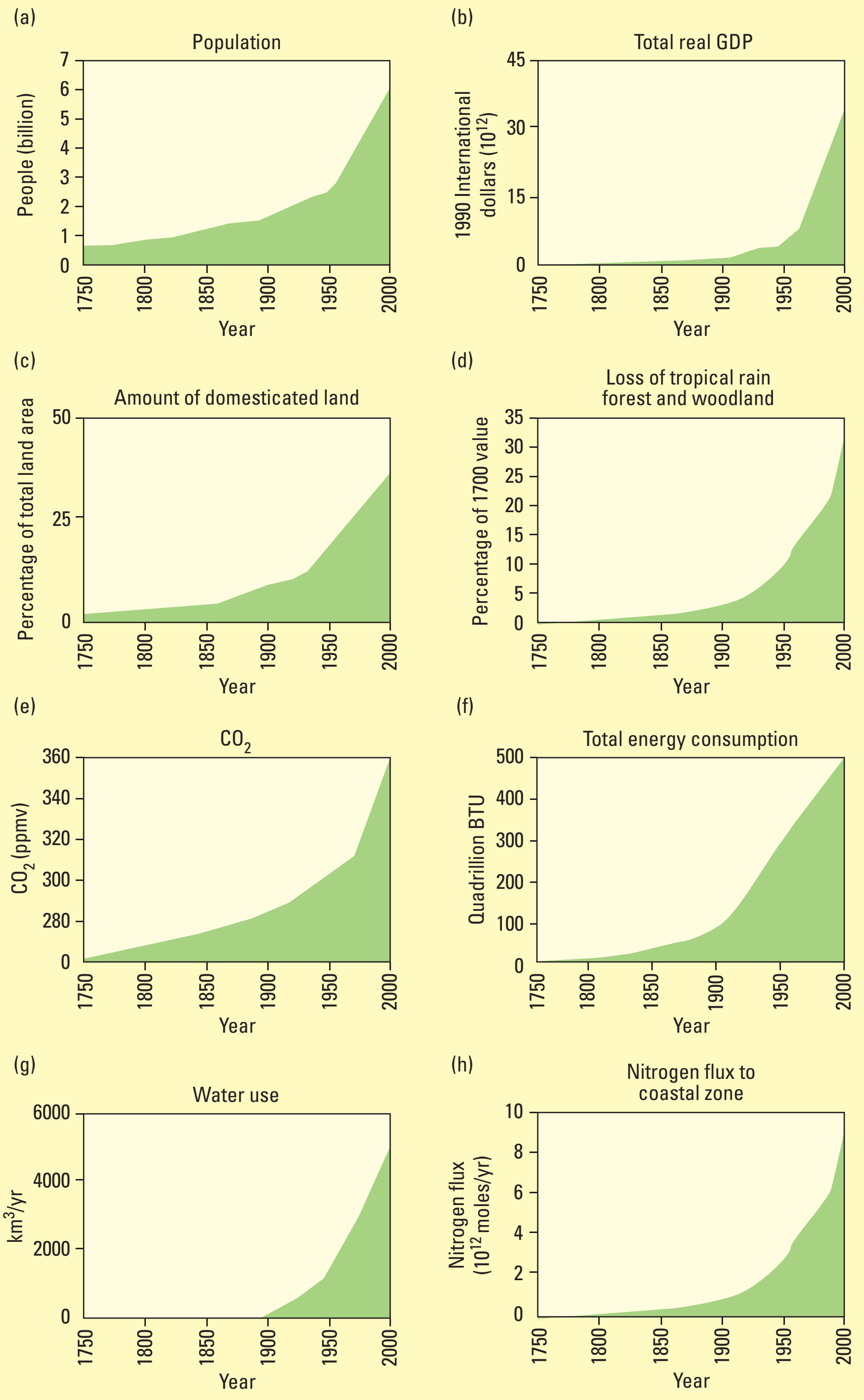
[1] Table SPM.1 in Ref. 12.

[2] These projections are for the 21st century and are based on the Special Report on Emissions Scenarios.

FIGURE 4

Global water stressors

Global trends over time of stressors (a–f) and the corresponding trends in water quantity and quality (g–h). (a–e, g, and h adapted with permission from Ref. 16; f adapted with permission from Ref. 13.)



ure 4 shows that changes are occurring on a global scale and, more importantly, that the rate of change is increasing. Furthermore, as shown in Figure 5, the spatial scale that will be affected by water-quality and -quantity challenges is also increasing. That is, the impacts of the stressors are increasing, and both the number of locations and the number of people that will be affected by these stressors in terms of water quality and quantity are increasing.

One challenge to both the scientific community and governments is that the impacts of global stressors are not independent (Table 2). The link between energy generation from fossil fuels and climate change is a clear example. Previously, we discussed the impacts that climate change, land use, and population have on water quality in terms of sedimentation. Another example would be that as the stress of globalization progresses, the external water footprints of many countries (the part of the footprint that is served by other countries) will become even more significant because of greater importation of goods and services. Similarly, as societies develop, they tend to increase water and energy consumption (*13*).

The stressors and impacts of the "hockey-stick world" to come suggest that we need to expand our design considerations in infrastructure systems for water and sanitation, which typically have useful lifetimes meant to last for decades (and often function beyond their designed lifetime). We also need to acknowledge that the conditions in which the design will function over its life cycle will take place in a world of rapid and increasing change. Recognition of this interconnectedness has led the African Development Bank and other development organizations (*14*) to agree that integrating adaptation responses into development planning, which includes improvements in water and sanitation, is an important way to address climate change impacts on the poor. For example, is a sanitary sewer an appropriate technology in a city that will become water-scarce by 2025? Sewers require on average up to 75 L/capita-day, whereas other sanitation technologies are available that require no water (*15*). Sewers can also distribute nutrients over a wide spatial scale, whereas other sanitation technologies can consolidate nutrients at the community level. And if a sewer project is deemed appropriate today, what should the community do to prepare for future ef-

TABLE 2

Current status of several global stressors on water resources and examples of the relationships between individual stressors

Stressor	Current situation (*13*)	Link to other stressors
Energy and climate	More than 82% of global energy demand was met by fossil fuels in 2004. CO_2 levels have risen to 380 ppm from preindustrial levels of 280 ppm.	The global impacts on the water cycle from human development stressors of changes in land cover, urbanization, and water-resources development may surpass impacts from recent or anticipated climate change (*17*). The stressor will result in greater variability in precipitation, and runoff will affect erosion and sedimentation, which is already impacted by land use.
Population	Current population is 6.7 billion with average annual growth rate of 1.4%. Of the world's 33 megacities, 21 are located in coastal areas.	During the next century, most of the 3 billion people added will live in urban areas. Large segments of the population are still impacted by water-related pathogens; this results in 64.4 million disability-adjusted life years (also known as DALYs). Just achieving the Millennium Development Goal for reducing hunger will require a doubling in agricultural water use by 2050. Climate-induced variability in precipitation and runoff will impact farmers dependent on rain-fed agriculture to a greater extent. Climate change affects the burden of disease due to malnutrition, diarrhea, and vector-borne diseases significantly more than it affects the risk associated with flooding or thermal extremes (*18*).
Land use	Approximately 50% of precipitation recharges to groundwater in a natural system, whereas only 15% recharges in a highly urbanized environment. Human changes in land cover increase runoff and sediment loading.	Current methods of urbanization result in loss of forested riparian cover along streams and increased flooding, sedimentation, dredging and filling of wetlands, and eutrophication.
Urbanization	Only half of the increase of the 100 largest urban areas in the U.S. from 1970 to 1990 was because of population growth.	Average population density in coastal areas is twice the global average, and the biodiversity of aquatic ecosystems continues to decline. Nitrogen loading is directly related to the loss of wetlands within an urban watershed. Urbanization leads to heat islands that influence energy use and climate.
Economic growth	By 2025, water withdrawals are predicted to increase from current levels by 50% in developing countries and 18% in developed countries.	Impact includes water used for energy production and increased use in both the nonconsumptive domestic sector and the consumptive industrial sector. One-half of the jobs worldwide are associated with water-dependent resources, such as fisheries, forests, and agriculture (*19*).

fects of climate change? These questions raise the issue of how to best meet basic human needs for water and sanitation, including technology selection and governance strategies, under increasingly variable and more water-scarce circumstances. They also raise broader questions of why we continue to design solutions that have an extended lifetime without considering the dynamic global conditions and the increasing rate of change.

Selecting technology in a dynamic world

Science must play a key role in solving present and future global water problems (*20*). Although significant advances have helped address water-quality and -quantity issues, many challenges still exist for technology research, development, and implementation. As these next-generation technologies are considered, the selection of those for further development and implementation ought to consider a broadened definition of performance to include improved water quality and quantity as well as energy and materials consumption, ecosystem function at the source and sink, life-cycle impacts, and human-health outcomes.

FIGURE 5

Freshwater concerns

Freshwater stress by country (top map) in 1995 and (bottom map) projected for 2025 (*13*).

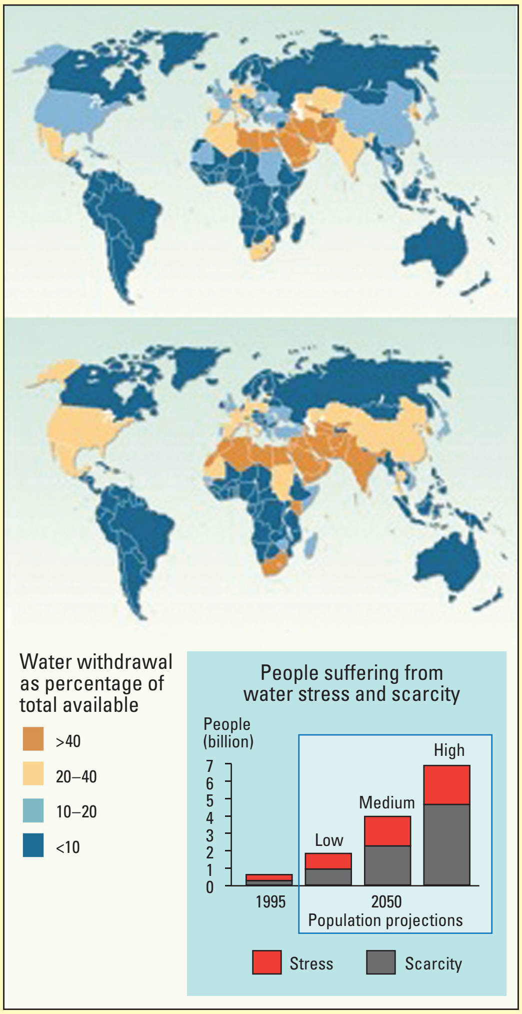


Table 3 provides a review of several technological opportunities and challenges associated with addressing the impacts of the global water stressors presented in Figure 4. Design methodologies and assessments that will adapt to fast rates of change in stressors and will integrate current and emerging global stressors need to be developed.

Developing governance strategies for a dynamic world

As with technology designs and selections, governance strategies should account for the dynamic global condition. These strategies, which will influence human behavior regarding water consumption and use, need to be able to support sustainable water systems under the scenario of multiple stressors and rapid rates of change. Governance strategies can have a significant influence over which technologies are pursued and on the amount of water consumed, recycled, and discharged and by whom.

For example, water-allocation systems are challenged by droughts, which can adversely affect human and natural systems. To address this problem, drought-management mechanisms have been instituted in jurisdictions around the world. Historically, these mechanisms have involved a crisis-management or reactive approach. An important trend during the past decade in places such as the U.S. has been a shift to a more proactive approach, emphasizing drought preparedness and local involvement (*26–28*). Water managers traditionally have maintained that consumers do not respond to price signals, so demand management has occurred most frequently through restrictions on specific water uses (i.e., banning car washing and lawn irrigation) and requirements for the adoption of specific technologies. In theory, raising prices to bring about water conservation is less costly than implementing a command-and-control approach, even if the prices in question are inefficient (*29*).

This example demonstrates the potential for expanded opportunities for governance options to encourage desired behavior in terms of water use; however, it also raises issues about setting the appropriate pricing scheme, because adjustments in cost may mean that certain segments of society or industry are “priced out” of the market, affecting local economic development. It also raises issues of fairness, because much of the global population is not currently served by adequate water sanitation and will need access to clean water to improve hygiene. Again, it is imperative to include considerations of sustainability outcomes and dynamic conditions when establishing long-term policies, that is, water allocation strategies, that can significantly influence water quality and quantity.

A review of several governance opportunities and challenges that can influence behavior and, subsequently, the human-dominated water stressors (Figure 4) is provided in Table 4. Like technological solutions, governance strategies established to address human behavior and water quality and quantity must also consider how the incentivized actions will relate to desired behavior under future conditions.

Conclusions

One challenge to solving global water problems is the large number and integrated impact of global stressors such as population and consumption, demographic and land-use changes, urbanization, and climate change. Another challenge is the rapid rate of change projected for all of these stressors and their resulting impacts, which are expected to accelerate even further over the next century. The large number of stressors, their unknown interrelations, and the observed rapid change must all be considered when selecting and adapting new technology and governance structures for sustainable water and sanitation systems.

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TABLE 3

Opportunities in technology and engineering and associated challenges

Opportunity	Current status	Challenge(s)
Desalination	More than 15,000 desalination plants operate in >125 countries, with a total daily capacity of 32.4 million m^3 of water (*21*).	Significant energy demands are required (e.g., a reverse-osmosis plant needs 1.5–2.5 kWh of electricity to produce 1 m^3 of water). Emissions from brine effluent Large global population located in water-stressed areas cannot afford the technology.
Long-distance water transfer	Water needs of Southern California require 770 mi of pipes and canals, 34 reservoirs, 20 pumping plants, 3 pump-generating plants, and 5 hydroelectric power plants.	Embodied energy and materials associated with transferring water and wastewater long distances are large over the life cycle. Water transfer can impact hydrology of local ecosystems at both the source and sink. Design of distributed wastewater treatment systems that conserve water resources, nutrients, and biogas potential within the watershed (*22*)
Water reclamation and reuse	Water-reuse capacity is expected to increase globally from 19.4 to 54.5 million m^3/day by 2015 (*23*).	Matching demand and supply as they relate to quality of treated water for a particular use and geographical location
Water efficiency/ substitution in engineering design	Industrial and agricultural sectors represent >80% of global water consumption (*24*).	Large water footprints in agriculture are caused by inappropriate water pricing, subsidies, inefficient technology, and the lack of water-saving measures (*5*). Decreasing embodied (virtual) water associated with process or product through disruptive or “leapfrog” innovations
Appropriate water technologies	Point-of-use treatment technologies provide a barrier to pathogen exposure and are a possible solution when centralized systems are ineffective or inappropriate (*25*).	Health improvement studies have largely ignored nondiarrhea water-borne diseases (e.g., typhoid, hepatitis A) and water-washed diseases (e.g., trachoma). Does not provide as many nonhealth benefits compared with source improvements, and noneconomic factors (e.g., compatibility, complexity) need to be integrated with adoption.

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TABLE 4

Examples of governance and economic issues associated with managing water

Governance strategy	Opportunities and challenges
Technology incentives	Interventions by governments through funding, purchase commitments, regulatory drivers, and voluntary programs can influence the success or failure of a given technology. Decisions to support certain technologies should consider performance under current and future conditions that integrate multiple stressors and acknowledge the rapid changes in stressors.
Water valuation	Population and other stressors will increase demand for water, which is currently undervalued relative to other scarce natural resources. Increases in population and wealth will shift demand among agricultural, industrial, and domestic sectors in many parts of the world; this will affect land use, energy demand, and climate change and, in turn, will impact water quantity, quality, and availability. Often much of the value of water is unaccounted for in the price (*30*). Full-cost water assessments require that the value be related to economic, environmental, and social (including health) benefits. By using the full cost of water to influence prices, the market can potentially contribute to sustainable water systems through innovations in efficiency, water substitution, and conservation to avoid higher costs. This will reduce the impacts of individual and combined stressors, thereby reducing demand.
Gray water regulations	Establishing dual water-quality standards (drinking water vs service water) can significantly enhance the adoption rate of water-recovery and -reuse systems. Because of the growing drivers for conservation, an opportunity exists to quantify the risks and benefits of water-reuse systems, define the appropriate scale, and develop regulations to support implementation. Management of gray water provides an opportunity to better manage nutrients primarily found in black water and to integrate the gray water resource with local agricultural activities. This can mitigate several stressors, including those related to providing food for a growing population through agriculture and land-use changes, by reducing the demand for freshwater and the energy related to water treatment through recycling and reuse.

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