Transitions to freshwater sustainability

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Fundamental transitions in natural resources technologies, institutions, and management approaches are often difficult to see in advance, or even in the midst, of actual changes. Such a transformation now appears to be underway for freshwater resources, driven by increasingly severe water-related crises around the world. These include mismatches between supply and demand; the continued failure to meet basic human needs for water and sanitation; expanding ecological degradation due to extraction of water from natural systems and human-caused climate changes; the development of new technologies for using, treating, monitoring, and reporting on water use; new conceptual work; and growing attention given to water issues by the public and scientific communities. Similar transitions, with additional implications for water, also appear to be underway in the energy and climate fields. For such transitions to be successful, it is important to understand what drives deep changes in the perceptions, management, and use of natural resources; the factors that encourage or discourage changes; and whether strategies can be developed to improve and accelerate those changes that lead to social, economic, and environmental sustainability goals. This paper addresses the concept of resource or environmental transitions in the context of freshwater; reviews theories, data, and frameworks for identifying and analyzing transitions; offers some examples; and identifies key policies to help manage effective and successful transitions.

water | freshwater | sustainability | transitions | peak water

Transitions are fundamental shifts in a policy, belief system, technology, institution, or management strategy from one baseline condition to a new one. Such a shift can occur abruptly or slowly, the pace of change can be linear or nonlinear, and there may or may not be a distinct threshold marking a change. One kind of transition occurs when an existing system becomes untenable or fails due to some combination of environmental, economic, social, and political conditions (1–3) or when incremental adaptations are inadequate (4). Other transitions may occur when a disruptive technology becomes available or when alternative systems or institutions develop that satisfy a new social need or priority. Evidence suggests that a major transition is underway for freshwater resources toward a more sustainable water future. This paper explores the idea of transitions in the management and use of freshwater resources, with the goal of offering insights into the ongoing shifts.

The Concept of Sustainability

There is an extensive literature on both "sustainability" and sustainable management of freshwater, extending back more than a quarter of a century to the Brundtland report for the United Nations World Commission on Environment and Development in 1987 (5). The US National Academy of Sciences has defined a field of Sustainability Science to facilitate what the National Research Council calls a "transition toward sustainability": improving society's capacity to use the Earth in ways that simultaneously "meet the needs of a much larger but stabilizing human population . . . and sustain the life support systems of the planet" (3, 6, 7).

Sustainability definitions are diverse, but they all share the following characteristics: The world should be considered a complex interactive system rather than isolated resources or processes; "time" should be considered a factor, giving weight to future generations as well as current ones; some form of resource renewability; and integrating natural resource and science issues with social, cultural, economic, and political factors.

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The focus here is on transitions in water resource use and management with the intention of reducing adverse impacts to the environment, economies, or social factors. Some resource transitions may, in fact, move in the opposite direction, worsening human and ecological impacts. For example, a desire to reduce political liabilities associated with imports of oil into North America, coupled with arguments that biomass-derived fuels could potentially reduce greenhouse gas emissions associated with petroleum production and combustion, led to decades of subsidies for ethanol production from corn feedstocks. Even if the initial assumptions about the relative costs and benefits of this strategy had been correct (which continues to be debated), unanticipated impacts on water demand, corn and food prices, and even social and political stability in some countries have led to calls to reconsider national ethanol policies (8, 9).

On the Need for Water Transitions

Human use of freshwater is influenced by three separate but related components: the natural hydrological cycle, which largely determines the availability and quality of water; the nature of human demands for water, which is a function of population size and social, cultural, and economic factors; and science, technology, and institutional factors, which provide practical tools and strategies for managing freshwater systems.

The unsustainability of current water systems is increasingly apparent. Numerous books, research papers, media reports, and organizations now address different aspects of freshwater crises (10, 11). A growing number of regions face "peak water" limits on water availability or growing water "scarcity," where surface supplies are completely allocated and consumed and groundwater systems are persistently overdrafted (12–14). Human consumption of water, or emissions of nutrient pollutants, exceeds sustainable limits during at least part of the year in more than half of the world's river basins (15). Human-caused climate changes are disrupting water policies and management strategies designed for stationary climatic conditions. Traditional economic and social institutions for providing water services have been unable to overcome the failure to provide universal access to basic needs for safe and affordable water and sanitation (16). An apparent increase in water-related violent conflicts in the past several decades at the subnational level highlights the lack of local and regional conflict resolution approaches, which have been more successful at the international level (17). In the face of these challenges and growing evidence that old models are failing, there have been calls for making 21st century water management more adaptive and flexible and for new ways of addressing water problems (1, 18–21).

Resource transitions happen when old models fail and when certain supporting conditions are present (1, 4, 22). These conditions include a change in physical or natural conditions, the failure of incremental adaptations, passing thresholds or tipping points, a change in demographic factors or social preferences, a change in technology or economics, exposition of a new paradigm, new kinds of social "networks," strong leadership or policy entrepreneurs, and political crises.

Changing Physical or Natural Conditions. Many water policies and technologies are created and implemented with the fundamental assumption that hydrological and climatic cycles are variable in the short term (extremes of weather) but static in the long term (stable climate). This is no longer true due to human-induced climatic change (23) and as the signal of climatic change rises above the noise of natural variability. Milly et al. (24), for example, wrote:

> Systems for management of water throughout the developed world have been designed and operated under the assumption of stationarity. Stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability—is a foundational concept that permeates training and practice in water-resource engineering . . . In view of the magnitude and ubiquity of the hydroclimatic change apparently now under way, however, we assert that stationarity is dead and should no longer serve as a central, default assumption in water-resource risk assessment and planning. Finding a suitable successor is crucial for human adaptation to changing climate.

This point has long been understood, albeit rarely acted upon; for example, a 1997 white paper prepared by the American Water Works Association (AWWA), which represents tens of thousands of managed water systems, stated: "While water management systems are often flexible, water agencies should re-examine water system designs and operating rules under a wider range of climatic conditions than traditionally used" (25).

Understanding how to do this, and implementing changes in inflexible organizations and institutions, remains highly challenging, but we are now entering an era when ignoring climate change in water planning and management is irresponsible. In the United Kingdom, the 2008 Climate Change Act established a requirement to assess the risks of present and predicted impacts, including on water resources, of climate change (26). In 2015, the US Environmental Protection Agency published a guide and recommendations for water utilities to address the growing threat of climate change, noting that "uncertainty should not prevent utilities from taking action now with regards to potential climate change impacts. For some utilities, it is not an option to wait and see or take no action. In fact, the cost of inaction may be greatly underestimated and can be offset by taking preventative action today" (27).

Passing Thresholds or Tipping Points. Institutional and management systems are designed to work under a given set of conditions. If thresholds are passed, however, fundamental changes can occur. There is substantial evidence of irreversible shifts by ecosystems from one regime to another when critical thresholds are exceeded (28–32). Early modeling studies of changes in runoff in the Colorado River basin due to climate change revealed that the changes could produce flood magnitudes exceeding all previously observed and anticipated extremes (33). Evaluation of a wide range of climate projections shows that abrupt reductions in Arctic sea ice can occur as global temperatures rise (34, 35), with far distant hydrological impacts on temperatures and precipitation patterns (36).

Ecosystem thresholds are also common, and water management decisions play a role in trying to prevent such thresholds from being crossed. In California, extensive water infrastructure was built over the past 150 years to serve multiple, often conflicting, priorities, including delivery of water to agricultural and urban users and maintenance of ecological processes and services. During the recent severe California drought between 2012 and 2016 (and increasingly even in hydrologically normal years), the system was unable to meet all expressed priorities. In the late summer and early fall of both 2014 and 2015, the lack of adequate surface flows and inappropriate management decisions led to sudden exceedances of critical thresholds, including temperature increases in the Sacramento River and the death in both years of ∼95% of the winter-run Chinook salmon populations, increasing the risks of extinction of this species (37).

Changing Demographic Factors. Demographic factors affect demand for water and water services. These factors include population size and age distribution, spatial distribution, and urban/rural differences, to name a few. The failure to meet basic needs for safe water and sanitation worldwide is now largely, although not entirely, a rural challenge. In the most recent assessment of the Joint Monitoring Program of the United Nations, 29% of the global population (2.1 billion people) lacked access to safely managed drinking water services in 2015. Sixty-one percent of the global population (4.5 billion people) lacked safely managed sanitation services. Globally, only 40% of rural populations use a piped water supply, compared with 80% of urban users. This urban/rural disparity is also evident for wastewater systems: 63% of urban populations have access to sewer connections, compared with only 9% of rural populations (16). The continuing transition worldwide to an increasingly urban population (Fig. 1) will influence progress in access to water services and is leading to a change in strategies for providing basic water services (38).

New Technology or Economic Factors. Changes in technology or economics also drive transitions in water systems. Among the most fundamental advances in human history was the development of engineering and construction expertise in ancient times to successfully transfer large volumes of water long distances to serve irrigation needs and growing cities (39, 40). One of the most important water-related technical transitions occurred early in the 20th century when science developed physical, chemical, and biological water and wastewater treatment systems capable of reducing or eliminating severe and persistent water-related diseases, such as cholera, dysentery, and typhoid (Fig. 2). Near the end of the 20th century, the development of sophisticated precision irrigation technology helped drive the fundamental (41) economic productivity of water use for food production while cutting overall water demand (42). The expansion of this technology worldwide has helped improve agricultural yields while holding total water demand constant or even reducing overall regional agricultural water use (43, 44). Numerous technical and economic transitions may now be occurring simultaneously. For example, a transition is underway in the development and application of sophisticated water treatment technologies that permit the direct reuse of previously unusable wastewaters (45, 46). Technological advances in remote sensing give scientists and managers more accurate real-time data. Smart water meters provide users with information about leaks and inefficient uses. Energy recovery and membrane advances are improving the economic viability of seawater desalination. Improvements in water pricing policies, such as innovative rate structures and reforms of subsidies, are sending more accurate economic signals to both water planners and users.

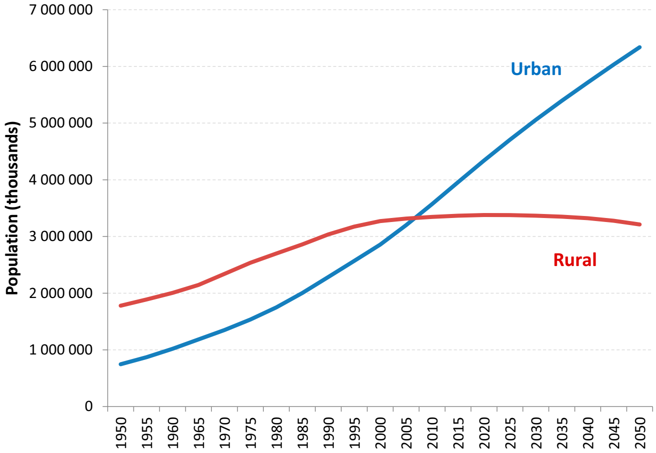

Fig. 1. Rural and urban populations, 1950–2050. In 2010, the world underwent a transition from a majority global rural population to a majority urban one, and the transition is continuing rapidly. Data from ref. 38, © 2014 United Nations. Reprinted with the permission of the United Nations.

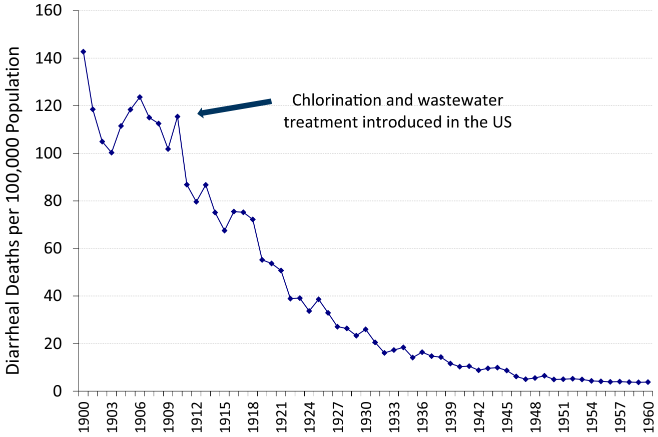

Fig. 2. Diarrheal death rates in the United States from 1900 to 1960 per 100,000 population showing the rapid drop associated with the development of urban water and wastewater treatment systems, which began to be introduced around 1909. Diarrheal death rates include both cholera and dysentery. Data from refs. 100 and 101.

Creation of New Approaches or Paradigms. Resource management works under a set of assumptions, beliefs, and paradigms that guide decisions. If physical or social conditions change, existing management systems can begin to fail. When this occurs, either severe consequences ensue, up to and including social collapse (47), or new ideas and approaches are developed to compensate, akin to paradigm shifts in scientific understanding (41). Effective social, technological, or management transitions are often hindered by the lack of adequate alternative frameworks; conversely, the development of such a framework can facilitate and accelerate needed transitions (48).

In the energy world, the early exposition of a "soft energy path" played a critical role in refocusing energy policy discussions (49). That new paradigm explored decentralizing energy supply systems in favor of alternative renewable, smaller scale, decentralized sources, combined with improving end-use efficiency and considering ecological and social measures in addition to simple financial ones.

A comparable transition in water is underway to address failures of current approaches that focus on how to satisfy projected demands without questioning the overall efficiency of resource use, acknowledging physical limits of expanded production, or understanding the broader social value or costs of what is being produced. New concepts, such as the "soft water path," refocus efforts on the multiple benefits water provides, improving water use efficiency, integrating new technology for decentralized water sources, modernizing management systems, committing to ecological restoration, and adopting more effective economic approaches (19, 50, 51). A piece of this transition to more sustainable water management was the adoption of the United Nations General Assembly Resolution supporting a human right to water and sanitation (52), followed by the more formal legally binding resolution of the United Nations Human Rights Council (53). After decades of debate, these resolutions explicitly recognized that clean drinking water and sanitation are essential to the broader realization of all human rights, and some countries and regions have put in place new laws and policies to implement the human right to water (54–56).

Social Preferences. As social mores and preferences change, consideration and implementation of new strategies, technologies, or policies become possible. One example is a shift in social preferences for outdoor landscaping, a key driver of urban water demand. In the western United States, the green lawn and traditional humid climate landscaping often accounts for more than half of all residential water use in a region. In arid and semiarid regions like the western United States, a hectare of turf can consume 10,000–30,000 m^3 of water a year, and in some homes, the amount of water used for lawns (typically high-quality and inexpensive potable water) can be far greater than the amount of water used for all other domestic purposes combined, including cooking, drinking, sanitation, and washing clothes and dishes.

These social preferences can change. During the severe drought in California between 2012 and 2016, there were increasingly urgent calls for reductions in urban water use, including limits on outdoor watering. Governor Jerry Brown issued an emergency order in early 2015 that called for the replacement of 4.6 million m^2 of lawns and ornamental turf with drought-tolerant landscapes. As part of the response to the drought, some water agencies offered advice and financial incentives to homeowners to help remove lawns, and there were growing calls for a permanent change in attitudes about the concept of appropriate and beautiful landscapes. Such a shift is occurring and is likely to lead to a permanent reduction over time in the amount of water used in residential landscaping (57).

New Social Networks. Information, advocacy strategies, water policies, academic ideas, and perceptions can be shared and spread through a variety of social networks. Transitions can be facilitated by expanding or altering these networks to provide new information or ways of influencing water policy. Many kinds of water networks have developed over decades, such as professional organizations like the International Water Association, the Desalination Association, the AWWA, and the American Water Resources Association, or scientific societies, such as the American Geophysical Union and the American Association for the Advancement of Science. These networks include thousands of individuals and groups and facilitate conferences and information-sharing across a wide variety of issues.

In recent years, new networks have been created, facilitated by easy Internet access and new forms of social media. They permit a large variety of individuals to share new ideas and information about water problems and policies, including ideas that were previously ignored, discounted, or excluded by traditional networks. For example, most traditional professional water groups have long focused on the construction of new infrastructure, such as dams, reservoirs, and aqueducts, as the top priority for finding new supply. As the limits and liabilities of these traditional approaches became better understood, some researchers and organizations shifted their focus to demand management tools and approaches long before mainstream networks of water planners and managers. In recent years, these approaches have proven to be economically and technically effective, and nontraditional networks (including groups like the Alliance for Water Efficiency, the Pacific Institute, and the US Water Alliance) have played an important role in promulgating them.

There has been some research into transformations supported by the emergence of informal networks that improve information flows, identify information gaps, and provide new "nodes of expertise." Such networks are typically politically independent of traditional groups and provide a safe place for new ideas to be tested (58) and new groups to be active. There is also a growing literature exploring social networks that link local communities with governmental agencies to build support for a transition to more integrated and effective ecosystem management (59, 60).

Leadership and Policy Entrepreneurs. Individuals in leadership positions can play a strong role in driving system changes and transitions. Like any factor, the effect of such individuals can be difficult to disentangle from other variables, but some researchers have noted important leadership influences (61, 62). In campaigns to put in place comprehensive ecosystem protections for the Florida Everglades, a few leading voices, such as Marjorie Stoneman Douglas (63), helped promote public understanding, create new networks, and mobilize public support (64). On the science side, leadership from ecologists and environmental scientists, such as Buzz Holling, Carl Walters, Lance Gunderson, Steve Davis, and Steve Light, provided early key arguments for protection.

Another classic example is the role that David Brower, Executive Director of the Sierra Club at the time, played in the mid-1960s in stopping the construction of large dams along the Colorado River that would have flooded the Grand Canyon. His efforts, while part of a broader campaign to alter the way western US water policy was implemented, have been recognized as key to a transition in how societies perceive the value of large water infrastructure compared with unimpaired ecological values (65).

Political Crises. Rapid change and ecological crises can precipitate political crises and play a role in accelerating water policy transitions by raising awareness, mobilizing broader networks, and promoting new governmental solutions (60, 62). Kingdon (66) argues that major transitions are most likely when problems are severe, plausible alternatives are available, and political conditions provide a "window of opportunity" for a change. Meijerink and Huitema (62) offer examples where policy entrepreneurs and the media built on environmental emergencies to raise awareness and political attention to both problems and alternative solutions. For example, changes in national and regional flood policies toward more ecosystem-based management and restoration of floodplains were pursued after severe flood events in Hungary, China, Germany, and Thailand. In the United States, the highly visible crises of burning oils on the Cuyahoga River and oil spills off the California coast in 1969 helped move the passage of key federal water quality legislation: the Clean Water Act and the Safe Drinking Water Act (67). Fundamental changes in groundwater law in California became possible only during a severe multiyear drought in California that altered the political landscape (68).

Examples of Major Water-Related Transitions

Rapid Technological Adoption of New Water Treatment in the Early 1900s. In the first decade of the 1900s, a dramatic and rapid change in water treatment occurred, driven by a combination of new science, technology, and financing tools. In the years between 1850 and 1900, major advances in the biological and medical sciences brought new understanding of the causes of water-related diseases and the development and application of new technologies. The classic story of John Snow and his linking of a contaminated well in London to recurring outbreaks of cholera led to a wider understanding of the need to dramatically improve water and wastewater handling (69). Following this early epidemiological research, cholera was confirmed to be a disease caused by a bacterium (*Vibrio cholera*). Similarly, the medical community identified the cause of typhoid fever to be the bacterium *Salmonella typhi*.

Both diseases are closely associated with contaminated drinking water and poor sanitation. As their biological origins were discovered, advances in water treatment technology were pursued and developed. In the 1890s, the use of chlorine to kill bacteria in drinking water systems was proposed, and by the early 1900s, water systems in England and the United States began using filtration and chlorination technologies (70). As details of the success of this approach spread, water suppliers in the developed world invested public funds in new urban water supply and treatment systems, leading to a rapid drop in death rates from water-related diseases. Fig. 2 shows the drop in diarrheal (cholera and dysentery) death rates in the United States starting around 1909, in deaths per 100,000 population. Data showing a similar reduction in typhoid death rates are presented in *SI Appendix*, Table S2. While these improvements are still lacking in wide parts of the world, they mark a fundamental transition in urban water systems, public perception of tap water, and public health improvements.

Integrated Resource Management. The idea of managing water resources in an integrated fashion is not new. Calls to consider water holistically rather than in a fragmented way, manage it with interdisciplinary tools and organizations, and include a wide range of voices in decision making go back many decades. The concept of more formalized tools in the form of integrated water resource management (IWRM) began to be discussed during large international water conferences, including the 1977 Mar del Plata meeting and the 1992 Dublin Water Conference (71, 72). While there have always been difficulties with precisely defining and implementing IWRM, the idea has been described as "a holistic, ecosystem-based approach which, at both strategic and local levels, is the best management approach to address growing water management challenges" (73). Now, IWRM is usually described as including the establishment of specific water policies and laws that use watersheds as the scale of management, establish water rights, use water pricing and other economic tools in allocation, and include wide participation in decision making (74). Despite criticisms about practical applications of IWRM, the concept of managing water in a far broader context than simple engineering solutions is now firmly entrenched and seems to mark an irreversible transition driven by the conceptualization of new approaches, a change in public awareness of the value of ecosystems, and leading voices in the water community.

Another example of new thinking around integrated resource management is the "nexus" concept. Until recently, and still in many places today, water, energy, food, and forest resources were managed by different agencies, institutions, and organizations that rarely or poorly interact. As the links among resources have become better understood, there has been a change in emphasis to try to identify and capture advantages that may result from joint management. The water–energy nexus, for example, is an effort to better understand the energy implications of water policies and practices and the water implications of energy choices, and to manage them together. Early work in this area focused on the water requirements of producing electricity in centralized power plants; later work looked at the broader water implications of full fuel cycles or competing energy policies (75–78). More recently, work in this area expanded to include efforts to better evaluate connections between water, energy, climate, and food systems (79–81).

Changes in Perceptions of the Quality, Value, and Utility of Wastewater. A key element in the ongoing water transition is a shift from a focus on traditional sources of supply that are increasingly costly or simply unavailable to alternative sources, including the reuse of high-quality treated wastewater. Modern water treatment technologies, which can include combinations of chemical, biological, and physical processes, are able to produce water of the purest quality and the US National Academy of Sciences concluded that the risk from potable reuse of highly treated wastewater "does not appear to be any higher, and may be orders of magnitude lower" than any risk from conventional treatment (82).

In the case of this transition, a critical factor has been peak water constraints: Water agencies are increasingly unable to find new traditional sources of water (12). However, changes in perception have also been needed: A simple technology shift, through the application of advanced treatment systems, has not been sufficient. A perception of treated wastewater as dirty or unsafe, which is often worsened by public campaigns ("toilet to tap" campaigns) against the use of treated wastewater, has hindered the ability of water agencies to add treated wastewater to their supply portfolios, especially in the form of additions to potable supply (83).

Singapore has been a policy leader in managing a transition to advanced treatment and reuse of wastewater. Singapore faces serious constraints on local water availability and the political liability of depending on a neighboring country (Malaysia) for a substantial fraction of its water supply. At the beginning of this effort, public concern and opposition to water reuse were common. To counter this, the Singapore Public Utilities Board launched an education program around its wastewater reuse plans, which it branded "NEWater." The program included a two-year scientific study to evaluate the quality of the water and possible health risks, which concluded that NEWater was "purer than tap water" (84). The utility followed up that study with public films, widespread advertisements, community discussions, and school information meetings, and the project has now been largely accepted by the public.

A combination of absolute water scarcity, improved treatment technology, and more sophisticated public communication has also helped transform public perception about water reuse in the western United States. In a 2004 public opinion survey conducted for the San Diego County Water Authority, there was public support for many uses of recycled water, but not for potable use (85). That idea was opposed by 63% (45% strongly) of those surveyed because of concerns and uncertainties about the process and possible health risks. By 2011, however, public opinion had begun to change. Seven years later, after educational programs, severe drought and growing water shortages, and the rising cost of alternatives, two-thirds (67%) of respondents either strongly favored (34%) or somewhat favored (33%) advanced treated recycled water as an addition to the supply of drinking water (86). By April 2015, during the fourth year of severe drought, 71% of respondents felt it is possible to purify recycled water to augment drinking water supplies and a similar number (73%) strongly or somewhat favored using advanced treated recycled water as an addition to the drinking water supply. These changes in perception are shown in *SI Appendix*, Fig. S1.

Shift in the Water Supply Paradigm: From Dam Construction to Dam Removal. In the western and southern United States, substantial public and federal investment contributed to the development of thousands of dams for hydroelectric, flood control, water supply, and irrigation purposes. Fig. 3 shows the cumulative volume of water stored behind reservoirs in the United States from the late 1800s to 2003. The Soviet Union saw a similar kind of expansion during this period, and China is undergoing such an expansion now.

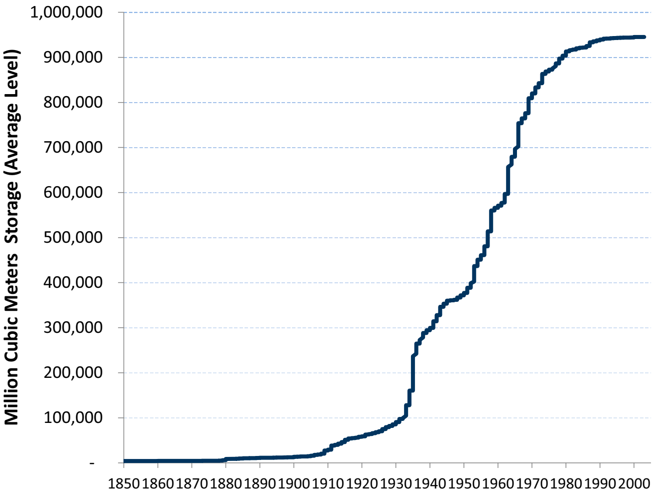

Fig. 3. Cumulative reservoir storage volume in the United States from 1850 to 2003, in million cubic meters. Data from ref. 102.

The rapid expansion of reservoir storage in the 20th century reflects several major drivers: the development of engineering expertise capable of building megadams in places previously thought impossible; the massive demand for electricity during World War II; and the push to expand agricultural production in California's Central Valley, coupled with the state's growing need for flood and drought protection and urban water supply.

Almost all major dam projects in the United States were built with federal funds. As more dams were built in the United States, and more of the nation's rivers and groundwater were consumed, it became increasingly difficult to find new traditional sources of water that were economically, politically, and environmentally acceptable, and by the end of the 20th century, the era of big dam construction had come to an end. New additions to US reservoir capacity in the past two decades have been relatively modest, and only small increments of additional storage are now being built (Fig. 3), reflecting a new reality for water and a transition from a focus on developing new supplies to better managing existing systems and water demands. This transition is the result of three key factors: growing restrictions on the availability of federal funding for water projects; a paucity of new high-quality dam sites; and growing public opposition to new large dams as our understanding of their impacts on rivers, wetlands, and aquatic ecosystems has improved.

SI Appendix, Fig. S2 shows federal spending on all water-related projects, including infrastructure, utilities, and water-related transportation in 2014 dollars and as a percentage of the total federal budget: Spending peaked in the late 1970s and has now dropped to under $18 billion a year and less than half a percent of the total federal budget (87). Moreover, less federal water spending is for capital projects and more is for annual maintenance.

We are witnessing not just a slowdown in the construction of new dams but a parallel trend in the decommissioning and removal of old, dangerous, ineffective, or especially damaging dams. Hundreds of mostly small dams have been removed in the past couple of decades, and efforts to remove or decommission some significantly larger ones are gaining influence (88).

Peak Water Use in the United States. An important and dramatic water transition is underway in the United States, and perhaps many other countries as well. This transition involves a fundamental change in the nature, characteristics, and dynamics of water demand in the form of a leveling off and then a decline in both absolute water withdrawals and per capita water use.

A core assumption of most classically trained resource planners and managers is that the demand for natural resources, such as water, energy, land, forestry products, and minerals, will rise in direct proportion to both the size of the economy and the population. This assumption drives all long-term planning for infrastructure and investment of financial resources for development. It has also been largely unchallenged by academics and policy makers alike. For a growing number of resources, in a growing number of regions, however, this assumption is no longer true because of the changing nature of technology, improving "productivity" of resource use, physically or economically determined limits on access to some resources, and dynamics of global trade.

Water use in the United States, defined as total withdrawals of water from surface and groundwater systems, greatly increased in the 20th century as populations grew and economic and industrial activity, as measured by gross domestic product (GDP), expanded. Fig. 4 shows the parallel growth in GDP and water withdrawals through the late 1970s. Beginning in the mid-1970s, however, while GDP continued to rise, water withdrawals leveled off and then began to decline. Fig. 5 shows indexed increases in water withdrawals, GDP, and population since 1900. Total water withdrawals peaked around 1980 at ~1.6 billion m^3 per day and have since declined to around 1.2 billion m^3 per day (89–92), representing a decline of 25%.

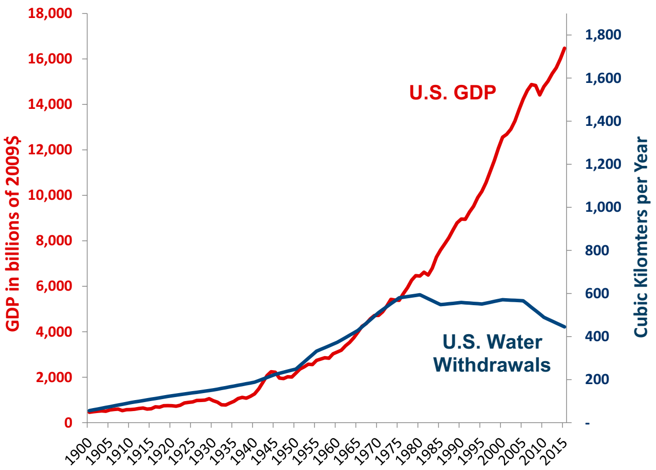

Fig. 4. Total US water withdrawals (blue line) in cubic kilometers per year and GDP (red line) in 2009 dollars, from 1900 to 2015. Data and details on sources are provided in *SI Appendix*, Table S3.

Per capita water use (for all purposes, including domestic, agricultural, energy, and industrial uses) in the United States has dropped even more from its peak in 1975 of 7.4 m^3 per person per day down to 3.8 m^3 per person per day in 2015. If each American still used the larger amount, total water demand would have grown by more than 390 km^3 annually, a volume equal to the annual flow of around 20 new Colorado Rivers, or enough water for everyone in California, New York, Florida, Texas, Illinois, and Michigan (67). Because of peak water limits, especially in the western United States where new water supplies from groundwater and rivers are largely unavailable, such traditional increases in demands would have been impossible to satisfy with traditional approaches (12).

This transition from an era of relentless hydrological expansion to one of steady-state or declining water use marks a new phase in resource management. As noted above, such transitions are sometimes difficult to see at the time, especially for changes that happen slowly and incrementally. However, several decades of data now support the idea of this change. Some of them were pointed out over a decade ago (e.g., ref. 93) as long-term data on total national water withdrawals and consumption started to accumulate. As new and updated data have become available, however, what might have been anomalous, short-term changes increasingly appear to be permanent.

The decoupling of water withdrawals from population and economic growth is occurring for three key reasons. First, substantial technological improvements driven, in part, by federal regulations on industrial wastewater discharges and by state and federal appliance efficiency standards have reduced the amount of water required to meet urban, industrial, and agricultural needs (e.g., *SI Appendix*, Table S5). Second, changes in the overall structure of the US economy have also played a role in this transition, including a shift in water-intensive manufacturing to overseas locations (67, 94, 95). Third, a change away from water-intensive once-through cooling systems for thermal power plants has reduced the amount of water required to produce a unit of energy. These observed changes in water use support the idea that the US economy has decoupled total water use and population and economic growth (96). A parallel example is the environmental Kuznets curve, which hypothesizes that environmental problems increase with economic growth until a point in industrial development and wealth when resources can be devoted to environmental protection (97).

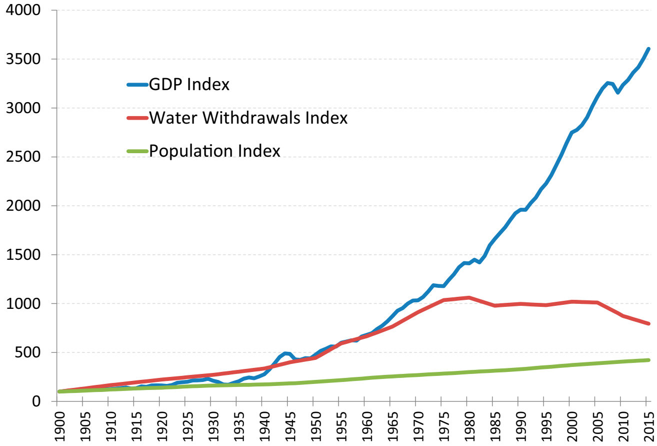

Fig. 5. **Indices of US GDP (blue line), water withdrawals (red line), and population (green line). 1900 = 100. Data and details on sources are provided in *SI Appendix*, Tables S3 and S4.**

Unsuccessful Transitions and Barriers to Transitions. Not all proposed or supported sustainability "transitions" are successful, and not all successful transitions are steps in the right direction. Barriers to transitions can include the difficulty of overcoming tradition and culture, antiquated laws and institutions, inertia in complex social systems, the long time required for changes in technology, inadequate financial investment, and more. Sometimes, individuals or groups with an interest in maintaining the status quo hold far more authority or power than those with an interest in implementing new approaches. For example, Te Boekhorst et al. (98) concluded that the introduction of the concept of IWRM in China was regarded as threatening the accepted Chinese approach focused on building large-scale hydroengineering projects.

The replacement of public water systems with private ones is another example of a failed transition: Large-scale water privatization was proposed as an alternative development model to address the lack of success in providing comprehensive safe and affordable water and sanitation before, and later as an explicit part of, the Millennium Development Goals at the United Nations. Early supporters of privatization approaches included the World Bank and multinational companies working in the water services area, which argued that greater financial and management efficiencies, reduced risks of corruption, access to new sources of capital, and other possible advantages could help turn around unsuccessful water systems. However, the concept ultimately failed to have the kind of effect its proponents hoped for because of a combination of factors, including an inability to prove sufficient economic and operational improvements over well-implemented public models, massive public opposition on the grounds of a lack of equity and transparency, and a preference for public over private control of water. A diverse mix of public and private systems remains a viable approach today (62, 99).

Challenges

A fundamental transition to new thinking, technologies, and strategies for sustainably managing water resources is underway. Many regions of the world are well endowed with freshwater, but its uneven temporal and spatial distribution has always posed management challenges. Based on the nature and severity of the current global water crisis, the growing threat of now unavoidable climatic changes, and the inability or failure of current water management systems and technologies to resolve these problems, current approaches are giving way to ones structured around broader integration of technical and nontechnical solutions, with the ability to be flexible and adaptive to rapidly changing economic, hydrological, and social conditions.

The shortcomings of current approaches in the context of peak water limits and economic, political, and environmental constraints have been well documented, and new approaches have been proposed. The broad outlines and specific details of an historical transition to new water management regimes have been described in various forms, such as "the soft path for water" or "integrated water resources management." In the context of the "soft path," the argument is made that:

> Twentieth-century water policies relied on the construction of massive infrastructure in the form of dams, aqueducts, pipelines, and complex centralized treatment plants to meet human demands. These facilities brought tremendous benefits to billions of people, but they also had serious and often unanticipated social, economic, and ecological costs. Many unsolved water problems remain, and past approaches no longer seem sufficient. A transition is under way to a "soft path" that complements centralized physical infrastructure with lower cost community-scale systems, decentralized and open decision-making, water markets and equitable pricing, application of efficient technology, and environmental protection." (19)

For a system to be able to adapt to rapid or unforeseen changes or to make successful transitions, the following observations for both the research communities and water managers and planners are key:

i) Physical and natural systems face new unprecedented conditions.
ii) New information and data must be collected and disseminated, including information on new tipping points and thresholds.
iii) Physical and social systems under stress must absorb and respond to new information and data.
iv) New ideas need to be tested and then integrated with or replace existing approaches; most transitions use a combination of bottom-up and top-down strategies.
v) Policy entrepreneurs, leaders, and new social networks can play a vital role in accelerating change and in overcoming institutional inertia.
vi) Early efforts to test alternative technologies and policies facilitate rapid implementation and scaling up of successes when crises arise or windows of opportunities open.

Growing political and violent conflicts over access and control of water, the continued inability to provide safe and affordable water and sanitation for all of the world's people, collapsing aquatic ecosystems, and the evidence for intensifying extreme hydrological events because of human-caused climate changes all underline the need to accelerate the ongoing freshwater transition. The speed, nature, and success of this transformation will ultimately depend on all of the factors discussed here and on the ability of policy makers, the research and academic world, and local communities to overcome barriers to desired changes.

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