Roadmap for sustainable water resources in southwestern North America

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Edited by Glen M. MacDonald, University of California, Los Angeles, CA, and accepted by the Editorial Board September 3, 2010 (received for review April 21, 2010)

The management of water resources in arid and semiarid areas has long been a challenge, from ancient Mesopotamia to the modern southwestern United States. As our understanding of the hydrological and climatological cycles has improved, and our ability to manipulate the hydrologic cycle has increased, so too have the challenges associated with managing a limited natural resource for a growing population. Modern civilization has made remarkable progress in water management in the past few centuries. Burgeoning cities now survive in desert regions, relying on a mix of simple and complex technologies and management systems to bring adequate water and remove wastewater. These systems have permitted agricultural production and urban concentrations to expand in regions previously thought to have inadequate moisture. However, evidence is also mounting that our current management and use of water is unsustainable. Physical, economic, and ecological limits constrain the development of new supplies and additional water withdrawals, even in regions not previously thought vulnerable to water constraints. New kinds of limits are forcing water managers and policy makers to rethink previous assumptions about population, technology, regional planning, and forms of development. In addition, new threats, especially the challenges posed by climatic changes, are now apparent. Sustainably managing and using water in arid and semiarid regions such as the southwestern United States will require new thinking about water in an interdisciplinary and integrated way. The good news is that a wide range of options suggest a roadmap for sustainable water management and use in the coming decades.

climate change | soft path | freshwater | sustainability | water management

Water management in arid and semiarid areas has long been a challenge, from ancient Mesopotamia to the modern time. Modern civilization has made remarkable progress in the past few centuries, especially in the area of resource mobilization, manipulation, and use. Scientific understanding of the hydrological and climatological cycles has improved dramatically in recent decades. Burgeoning cities now survive in desert regions, relying on simple and complex technologies and management systems to bring adequate water and remove wastewater. Agricultural production has expanded in regions previously thought to have inadequate moisture. Sources of water that were unusable because of high cost or low quality increasingly satisfy a wide variety of human needs.

However, evidence is also mounting that our current management and use of water is unsustainable. The resource issue that is going to be most difficult to address in the western United States is not land, or energy, or mining, or climate, but water, which ties each of these other resource challenges together. It takes supplemental irrigation to produce food; climate changes will alter the hydrologic cycle; substantial energy is required to move, treat, and use our water; and substantial quantities of water are required to help us satisfy our energy needs. Economic and environmental limits to additional water withdrawals, even in regions not previously thought vulnerable to water constraints, are now apparent. In the world's drier regions, real limits are appearing that are forcing water managers and policy makers to rethink previous assumptions about population, regional planning, and forms of development. In addition, new threats, especially the challenges posed by climatic changes, are accelerating the need for new ways of managing water.

Nowhere is this more apparent than in the southwestern United States—a region with an arid and semiarid climate, limited water resources, and a growing population. Even without the threat of climate change, this region has always faced special difficulties with sustainable management of water. Psychologically and socially, it is hard for millions of people who love this region to admit that it is fundamentally dry and that the rules for building, living, and working there must be different from those in the wet regions where most of them were born and raised. More than a century of reclamation has remade the map of the west, replumbing nearly every river with massive reservoirs, diversions, irrigation systems, hydroelectric plants, and flood-control structures. The wild, dangerous Colorado River, explored in fear and wonder by John Wesley Powell and his party 150 years ago, is a tamed beast today, suitable for rafts of families and thrill-seeking urbanites, blue instead of Colorado red because its sediment is stripped and settled in massive reservoirs, and its flows diverted and controlled. Evidence that the old river is still alive appears now and then, as we saw in the great winter of 1983 when Glen Canyon Dam itself was threatened with destruction by flood flows. Nevertheless, the waters of the west have been remade to serve humanity.

These efforts brought important economic and social benefits. However, the systems we have built are unsustainable without fundamental change. It is now apparent that ecosystems are collapsing under the modifications imposed upon them, from the introduction of invasive species to modifications of water flow, timing, and quality (1, 2). Unconstrained and unmanaged growth in southwestern cities and suburbs can no longer be accommodated from the perspective of water supply. The irrigation of certain crops in certain places no longer makes sense, even with economic subsidy. Furthermore, the style of urban water use can no longer mimic eastern US or European traditions but must be more attuned to the hydrologic realities of the region. On top of these challenges, the realities of coming climate changes add even more pressure to rethink the strategies used for water management for the past 150 y.

Water Management Strategies: Old and New

In the 20th century, water policies adopted by resource managers at all levels reflected the prevailing management philosophy of the time: build large-scale, centralized, federally subsidized infrastructure to move water in both space and time to meet current and projected demands. In the

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Author contributions: P.H.G. designed research, performed research, analyzed data, and wrote the paper.

The author declares no conflict of interest.

This article is a PNAS Direct Submission. G.M.M. is a guest editor invited by the Editorial Board.

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www.pnas.org/cgi/doi/10.1073/pnas.1005473107

western United States, where natural aridity limited perennial water resources to selected areas, this meant building dams and aqueduct systems on a scale unprecedented in human history. That story has been described in a number of superb popular accounts (3–5). By the early 1990s, the world's largest dams had been constructed on the Colorado, Columbia, Sacramento, San Joaquin, and other major western rivers. The entire annual average flow—and perhaps even more—of the Colorado River had been allocated to the seven states and Mexico under a complex set of legal agreements. Billions of cubic meters of water (millions of acre-feet) are now flowing out of the basin itself to southern coastal California and other regions; and agricultural production has skyrocketed through the development of semiarid land irrigation systems.

These changes were driven by the philosophy that government-subsidized water development was necessary to help support, and even encourage, population expansion and economic growth in the region. Between 1920 and 2000, population growth in the seven states that share the Colorado River grew 762% (Fig. 1), and today the basin supports 50 million people, 92% of whom live in urban areas. Between 2000 and 2030, the population in this basin is expected to grow by another 23 million people (6).

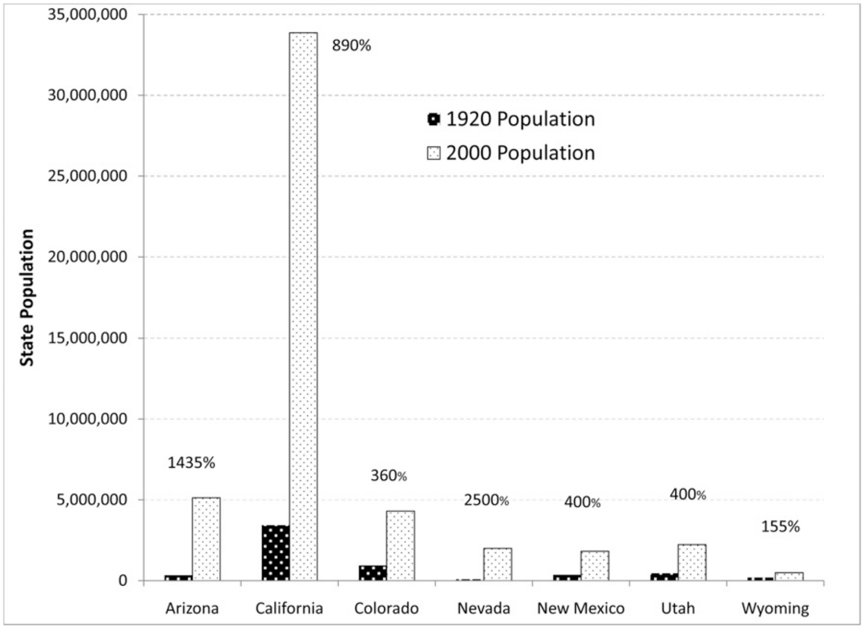

Fig. 1. Population of the seven states that share the Colorado River has risen more than 750% between 1920 and 2000 (7, 8).

The 20th century approaches used to deal with water challenges are now failing, and new thinking and management approaches are needed. Part of the problem is that the region is literally running out of traditional supply options, and there is limited ability to continue to apply the solutions that worked in the past. Limits on traditional supply are the result of both physical and political/economic constraints. On the physical side, there are fewer and fewer feasible options for expanding supply. The Colorado River and related southwestern water systems are reaching their peak renewable limits, making it impossible to withdraw additional supplies (9). "Peak renewable water" limits are reached when the entire renewable supply of a watershed is appropriated for human use. On the Colorado River, such limits were reached many years ago when legal allocations exceeded the long-term average reliable supply. On the political and economic side, the support for expanding traditional water systems has largely evaporated along with the federal funding that fueled the original expansion. With the loss of national subsidies for new large-scale water systems of any kind, the financial burden for new water projects is falling on local users, who are themselves financially constrained.

Second, the current approaches have had serious ecological side effects that were either ignored or unanticipated when our original water systems were designed and built. Every major aquatic ecosystem in the region is under stress and reaching or exceeding peak ecological limits (9). "Peak ecological water" is the point at which additional water withdrawals cause more ecological harm than they provide ecological benefit. These limits are evident in the Colorado River delta, the Salt, Verde, Gila, Santa Cruz, Rio Grande, and other rivers flowing, or formerly flowing, through urban areas of the region, and in impacts to coastal fisheries from Mexico to Alaska.

Third, there are growing conflicts among water users: cities are increasingly competing with farms; growers are competing with other growers; water required for energy development is competing with water for other industrial and economic priorities; and transboundary issues continue to be a concern with Mexico. The tensions are increasingly strong around energy development. Traditional energy systems, in particular thermal power plants that use fossil or nuclear fuels, require substantial water for cooling. Some new renewable energy developments, such as central solar thermal systems and expanded production of biofuels, may also have high water demands. Yet plans for energy developments in the southwestern United States have not fully taken such water requirements into account, raising new questions about competition for limited water resources (10). Such tensions are an indication of physical water constraints and the realization that the water demands from new development or growth will only be satisfied by reallocating water from existing users.

Fourth, future hydrologic conditions have been called into question by research into anticipated and observed climatic changes. The hydrology of the southwestern United States is already characterized by strong variability on seasonal to multiannual time scales, reflecting its sensitivity to fluctuations in large-scale atmospheric circulation patterns from the Pacific Ocean, the Gulf of California, and the Gulf of Mexico. Given this climatic sensitivity, it should be no surprise that the region has been the focus of extensive climate research. Some of the earliest efforts to understand the impacts of climate change for water resources have looked at the Colorado River system, hydrology, and operations. In the early and mid-1980s, research began to suggest that even modest changes in average streamflow caused by rising temperatures, changes in precipitation patterns, and accelerated snowmelt runoff would put pressures on both natural hydrological conditions and on the human systems built to manage both water supply and satisfy demand (11–15).

As Cayan et al. (16), Woodhouse et al. (17), and Seager et al. (18) show, current climate model simulations suggest that the region is likely to become drier and experience more frequent droughts over the next several decades, with changes accelerating toward the end of the century. The principal mechanism for these changes is accelerating warming with associated dry periods, changing storm dynamics off the oceans, increased soil-moisture deficits in spring and summer, and reduced spring snowpack and accelerated spring snow melt. However, general circulation model projections also suggest a trend toward the reduction in overall precipitation in lower latitude, continental regions. It is, of course, possible that climatic changes could lead to a reduction in pressures over water, if such changes increase overall availability in a form that can be captured and used. Unfortunately, current research suggests the risks are higher that water availability will worsen, not improve.

There is also evidence that anthropogenic climate changes are already apparent. Although in some parts of the Southwest recent extensive droughts have not yet been as bad as the most severe droughts on record, experienced during the medieval periods in the 1100s, temperatures are almost certainly higher now (17). Moreover, hydrological changes observed in the region over the several decades cannot be fully explained by natural variability (19–22). As the National Assessment concluded more than a decade ago in 2000, “The evidence that humans are changing the water cycle of the United States is increasingly compelling” (23).

Given the precarious water balances in the region already, any significant changes in either timing or availability of water can lead to disruptions and a potential worsening of tensions over water, as well as important changes in ecosystem dynamics. For example, severe dryness and warmer temperatures can accelerate insect pest infestations, which in turn can accelerate conifer tree die-offs (24, 25). Forest wildfire increases have been attributed to accelerated spring snowmelt and higher spring and summer temperatures (26); and future climate changes are projected to increase the frequency and impact of wildfires in the Southwest (27).

Moving to Solutions

To address the water problems facing the southwestern United States or any region of the world facing water challenges, new thinking and management are required. Below are four key strategies for a sustainable roadmap for water; water managers, planners, and utilities must rethink assumptions and definitions about water supply, work to reduce water demand through conservation and efficiency programs, develop improved systems for managing water, and integrate climate change into all water system decisions. A wide variety of tools for making these changes are possible, including new technology, economic approaches, regulatory requirements, and education.

Rethinking Water Supply

Traditional sources of water are increasingly expensive and scarce or are limited by political and social opposition. However, there are new opportunities for rethinking supply options. In particular, sources of water that were previously ignored or unusable now are being considered or tapped, including the desalination of brackish groundwater, reuse of treated wastewater, and rainwater harvesting. The town of Prescott Valley, Arizona, for example, has for many years used highly treated wastewater to irrigate local golf courses and to recharge groundwater aquifers. Recently the town proposed selling permits to its future supply of treated effluent to developers who need to show they have a proven source of water before they can build new homes. The water would continue to recharge groundwater aquifers, but the permits would permit new groundwater withdrawals. Another example of water reuse in the region is the Palo Verde nuclear power plant, which is the only plant to use reclaimed wastewater for its cooling system. Other innovative groundwater recharge and reuse projects are being developed throughout the western United States.

There are other efforts underway to use water-purification technologies to tap into previous unused or unusable sources of water. The city of El Paso has recently completed construction of the world’s largest inland brackish water desalination plant. The desalination plant uses reverse osmosis membranes to produce potable water from brackish water drawn from the Hueco Bolson, a local groundwater aquifer. Raw water passes through reverse osmosis membranes that separate salts and other contaminants from the water. The source water has a total dissolved solids (TDS) content of between 1,200 and 1,500 mg/L, and the plant produces water of 700–800 mg/L TDS, comparable to existing water quality. Approximately 83% of the water is recovered, leaving 17% brine concentrate for disposal in deep underground saline aquifers (28).

This project produces 10,400 m^3/d (27.5 million gal/d) of water for the El Paso region and has increased total fresh water availability to El Paso Water Utility by approximately 25%. The utility has also included in its strategic plan a goal of reusing 15% of its treated wastewater by 2017, and it has worked to improve overall water use efficiency in the district. Between 1977 and 2006, utility efforts to increase efficiency resulted in a drop in per-capita water use from 0.9 cubic meters per day to approximately 0.52 (or from 230 gal per person per day to 137 gal per person per day) (28). No comprehensive analysis for the southwestern United States has been done to evaluate the potential for alternative sources of supply to expand water availability or to permit some existing uses to be cut back to restore ecosystem flows, but as water becomes increasingly scarce and expensive, these alternatives will become increasingly attractive.

Rethinking Water Demand

Given the limitations on water supply and the high costs of developing alternative sources of water, one of the most important tools for reducing pressure on water resources is improving the efficiency of existing water uses. Water agencies have traditionally assumed that demand for water must increase exponentially with population growth and the economy. This assumption is false. In more and more regions, water demand has been constant or decreasing in recent decades due to increasingly sophisticated and effective conservation and efficiency efforts, even with growing population. The ability to cut water demand without affecting economic productivity remains very high (29).

A key to improving efficiency is understanding where, when, and why we use water. We use water for many things, from the production of food and industrial goods to cooling power plants and satisfying basic household needs. Almost all of these things can be accomplished with less water than we use today.

Substantial amounts of water are used in the southwestern United States to grow food. In California, Arizona, and most western states where pressures on water are especially intense, up to 80% of total water use is consumed by irrigated agriculture (30). A recent analysis in California suggested that more food could be grown with less water by improving irrigation technology and application, and these lessons are applicable throughout the Southwest (31). Installing efficient irrigation technologies, such as drip systems and improved soil moisture monitoring and management, can reduce water use and increase agricultural yield. However, nearly 50% of all crops in California are still grown with inefficient flood irrigation. Converting these crops, particularly vineyards, orchards, and vegetables, to more efficient drip and microsprinklers, could save a significant volume of water, while increasing agricultural production and income.

Improvements in nonagricultural water-use efficiency are also possible through more widespread distribution of residential appliances, such as washing machines, toilets, showerheads, and dishwashers, better outdoor landscape irrigation programs, and a wide range of technologies to reduce water needs in commercial and industrial settings. For example, the amount of water required to make steel has dropped from 200 tons of water per ton of steel 75 y ago down to 20 tons of water per ton of steel in the 1980s, and to 3 in

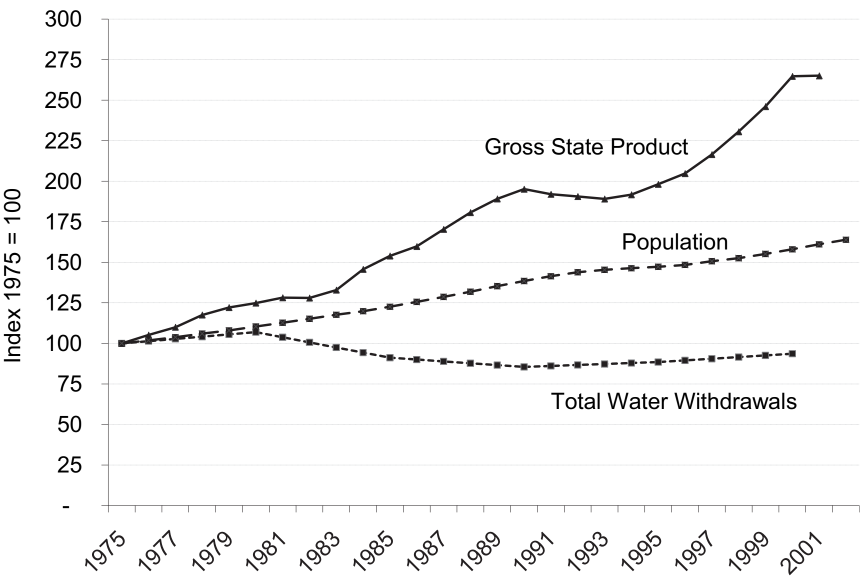

Fig. 2. Index of California's water use (green line), population (red line), and gross state product (GSP) (blue line) between 1975 and 2001. (1975 = 100.) GSP has gone up more than 2.5 times, whereas water use has actually declined. From the US Geological Survey (33).

the best steel plants today. Water required to process milk (gallons of water per gallon of milk) has dropped from 6 gal of water per gallon of milk down to just over 1 gal today. Semiconductors used to require 30 gal/in^2; now they require less than 6 gal (29, 32).

Many states and municipalities in the western United States have reduced inefficient water use, as has the nation as a whole. Total water use in California, and in the United States overall, was less in 2000 than it was in 1975, yet population and gross domestic product over that same period increased (Fig. 2). Despite these improvements, available cost-effective technologies and policies can further reduce urban and agricultural demand significantly. In the western United States more and more urban areas are faced with the option of investing in increasingly expensive new sources of water or developing policies to improve water efficiency. For example, the city of Las Vegas is seriously considering building a new multibillion dollar pipeline to rural counties to the north to tap groundwater, yet a recent analysis showed that local efficiency improvements can reduce demand by almost the same amount—approximately 86,000 acre-feet per year—at a cost far below that of the pipeline (34). Other western cities also have growing successful experience with these new conservation and efficiency approaches to water management (35).

Further progress in sustainable water management will require us to get even more efficient and eliminate more wasteful uses of water. Fortunately, the potential to do so is vast, particularly in regions such as the southwestern United States, where substantial amounts of water are still used for outdoor landscaping in urban areas and for irrigated agriculture. Fig. 3 shows the current single-family residential water use for several western water districts that have already invested substantial effort in improving water use efficiency. Yet many western cities have water use far above these levels. It would be helpful to establish incentives for improving water efficiency and reducing wasteful use of water at all levels, using a range of financial, regulatory, and educational tools.

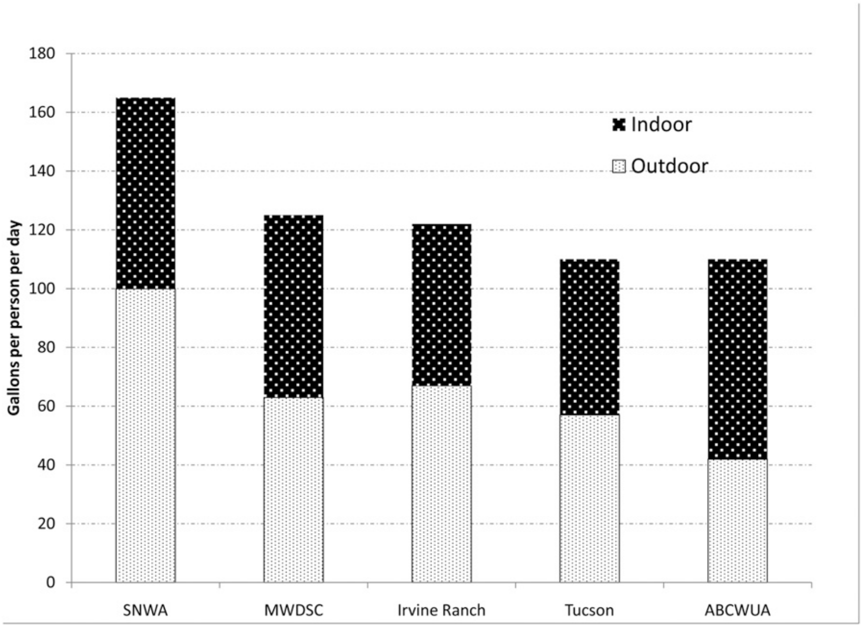

Fig. 3. Single-family residential water use, in gallons per person per day, separated by indoor and outdoor use, for five western water agencies: Southern Nevada Water Authority (SNWA), Metropolitan Water District of Southern California (MWDSC), Irvine Ranch Water District, and the water districts serving Tucson, Arizona and Albuquerque, New Mexico (ABCWUA). From Cooley et al. (34).

Improving Institutional Management

Increasing nontraditional water supplies and reducing demands through efficiency improvements are necessary elements for improving the water situation in the Southwest, but they are not sufficient. We do not manage water well in most places. New arrangements, especially in terms of improved clarity of federal/state responsibilities, can reduce pressures on water. For example, integrating state/federal management of projects in California's Central Valley, the Columbia Basin, and the Colorado would improve flexibility to meet conflicting and competing needs. More cooperative state-to-state water efforts would also help; for example, Nevada and Utah are facing a prolonged legal battle over shared groundwater basins because there is little experience in cooperative transbasin groundwater management.

Sustainable water management is also hindered by the lack of coordination among federal, state, local, and nongovernmental entities. At the national level, more than 20 different federal agencies share responsibility for various water resource issues, and larger numbers of state, local, and nongovernmental actors also play important management roles (Table 1). It would be helpful to

Table 1. Partial list of state, federal, and nongovernmental organizations with responsibility for western water policy

- Federal agencies
  - Departments of:
    - Interior
    - Commerce
    - Energy
    - Agriculture
    - Defense
  - Environmental Protection Agency
  - Bureau of Reclamation
  - Fish and Wildlife Service
  - National Park Service
  - US Geological Survey
  - National Weather Service
  - National Oceanic and Atmospheric Administration
  - National Marine Fisheries Service
  - Forest Service
  - Natural Resources Conservation Service
  - Army Corps of Engineers
  - National Institutes of Health
  - National Science Foundation
  - White House Office of Science, Technology, Policy
  - NASA
  - Food and Drug Administration
  - Federal Energy Regulatory Commission
- Congressional committees
  - Energy and Commerce
  - Natural Resources
  - Science
  - Agriculture
  - Armed Services
- Regional/state entities
  - State climatologists
  - State water agencies
  - Water resources research institutes
  - Western States Water Council
  - Western Governors Association
- Nonprofits, educational, community groups
  - Universities: The Consortium of Universities for the Advancement of Hydrologic Science
  - Watershed councils
  - Environmental advocacy groups (Environmental Defense Fund, Natural Resources Defense Council, Sierra Club)
  - Research and policy institutes (Pacific Institute, Sonoran Institute, Natural Heritage)
  - Land, water, and wildlife conservancies (Nature Conservancy, Trust for Public Land, Oregon Freshwater Trust, Trout Unlimited, Ducks Unlimited)
- Water agencies and associations
  - Association of Metropolitan Water Agencies
  - Water Utility Climate Alliance
  - American Water Works Association
  - Water Environment Federation
  - National Association of Water Companies
  - National Association of Clean Water Agencies
  - National Groundwater Association
  - National Rural Water Association

reorganize and streamline the diverse and uncoordinated water responsibilities.

Any roadmap for sustainable water management and use requires comprehensive and up-to-date information and data on water availability and especially water use. At present, these data are not available. The failure to monitor and measure all water use is an archaic holdover from the early days of western water policy, and it seriously hinders rational water management. Accurate and reliable data on water use are vital for evaluating the efficiency of current use, establishing efficiency targets, and evaluating performance toward meeting those targets. Furthermore, metering and charging for water according to the volume of water consumed are among the most effective tools for encouraging efficiency.

In many parts of the west, water meters are not yet required in the agricultural sector. As a result of the lack of monitoring, water agencies have a poor understanding about actual agricultural water use, particularly groundwater use.

As part of improving the management of water systems, there also needs to be substantial improvement in how we set, monitor, and enforce water quality laws. There are new health and safety threats to water systems, and current federal and state regulatory oversight are inadequate. In particular, new chemical threats to drinking water and to groundwater aquifers are poorly understood and regulated.

Integrating Climate Change

Climate change impacts should be integrated into all federal and state water decisions, planning, and management, including new construction and the operation of existing water systems, reservoirs, and watersheds. As described above, climate change will alter the supply of and demand for water in coming years. More and more states are addressing climate change, looking at impacts and consequences for water systems, as well as working to reduce greenhouse gas emissions, including those associated with water systems. California’s Department of Water Resources 5-y water plan calls for integrating climate change into all planning efforts. Senate Bill 193 in Oregon calls for the state’s water resources strategy to develop plans “related to the challenges presented by climate change.” The Seattle Public Utilities has developed plans to “understand the potential impacts of climate change on the systems we manage and to develop appropriate adaptation and greenhouse gas mitigation strategies.” However, far more needs to be done for major river basins, such as the Colorado, that have been shown to be vulnerable to even slight changes in climate, and where management is complicated by overlapping and often conflicting state, federal, and local jurisdictions.

A variety of actions are available to reduce the potential impacts of climate change. Many of these, such as efficiency improvements, provide social, economic, and environmental benefits regardless of the nature of climate change impacts. For example, an analysis on the impacts of climate change on the Boston water system found that supply deficits resulting from climate change, combined with increases in demand resulting from continued population growth, could cost as much as $700 million. Implementing water conservation and efficiency improvements, however, would reduce this cost to less than $150 million (36). In the western United

States, more and more integrated efforts to work with climate scientists, water agencies, utilities, and regional authorities are underway, such as the collaborative efforts between the American Water Works Association, Association of Metropolitan Water Agencies, Water Utility Climate Alliance, Western Urban Water Coalition, and water operators and urban agencies in the Pacific Northwest (37, 38).

Conclusions

We are entering a new era in water management. For regions like the southwestern United States, where water resources are especially scarce and where climatic changes may cause significant changes in water availability, quality, and demand, new approaches are needed to help us to simultaneously meet human and environmental demands for water. Signs of such new approaches can be seen in more and more places, from urban areas implementing aggressive water-conservation and efficiency programs to the efforts of innovative farmers to improve productivity without increasing water requirements. However, such changes are slow in coming: vested interests, outdated institutions, and restrictive and inflexible water laws make a new "roadmap" easier to see than to implement. Four broad categories of changes are needed: (*i*) an expanded concept of "supply" that encourages the development of new, untraditional sources of water, such as advanced treatment and reuse of wastewater, desalination of brackish water, and rainwater harvesting, rather than simply focusing on new dams, unsustainable groundwater overdraft, and additional interbasin transfers; (*ii*) a shift from a focus on supply to one that evaluates and manages water "demand," including policies that encourage major improvements in water-use efficiency to help maintain the economic value produced by water use while reducing total water use; (*iii*) new institutional approaches for integrating federal, state, and local efforts; and (*iv*) efforts to evaluate and adapt to the now unavoidable impacts of climate changes on water systems. These new approaches have been used successfully here and there in the western United States and offer a way to effectively move toward water sustainability, but they have yet to be adopted in a comprehensive and widespread manner.

1. Olden JD, LeRoy Poff N, Bestgen KR (2006) Life-history strategies predict fish invasions and extirpations in the Colorado River Basin. *Ecol Monogr* 76:25–40.
2. Mueller GA (2005) Predatory fish removal and native fish recovery in the Colorado River mainstem: What have we learned? *Fisheries* 30:10–19.
3. Worster D (1985) *Rivers of Empire* (Pantheon Books, New York).
4. Reisner M (1986) *Cadillac Desert: The American West and Its Disappearing Water* (Penguin/Viking Press, New York).
5. Hundley N, Jr (1992) *The Great Thirst: Californians and Water, 1770s-1990s* (Univ of California Press, Berkeley).
6. Gober PA, Kirkwood CW (2010) Vulnerability assessment of climate-induced water shortage in Phoenix. *Proc Natl Acad Sci USA* 107:21295–21299.
7. US Census Bureau*Census of the United States*. Available at: http://www2.census.gov/prod2/decennial/documents/41084484v1ch1.pdf. Accessed September 21, 2010.
8. US Census Bureau (2010) State population data. Available at http://quickfacts.census.gov/qfd/index.html. Accessed September 21, 2010.
9. Gleick PH, Palaniappan M (2010) Peak water limits to freshwater withdrawal and use. *Proc Natl Acad Sci USA* 107:11155–11162.
10. Elcock D (2010) Future U.S. water consumption: The role of energy production. *J Am Water Resour Assoc* 46:447–460.
11. Nemec J, Schaake J (1982) Sensitivity of water resource systems to climate variation. *Hydrolog Sci J* 27:327–343.
12. Revelle RR, Waggoner PE (1983) Effects of a carbon dioxide-induced climatic change on water supplies in the western United States. *Changing Climate* (National Academy of Sciences, National Academy Press, Washington, DC) , pages 419–432.
13. Rind D, Lebedeff S (1984) *Potential Climatic Impacts of Increasing Atmospheric CO_2 With Emphasis on Water Availability and Hydrology in the United States* (Government Printing Office, Washington, DC).
14. Gleick PH (1987) Regional hydrologic consequences of increases in atmospheric carbon dioxide and other trace gases. *Climatic Change* 10:137–161.
15. Gleick PH (1988) The effects of future climatic changes on international water resources: The Colorado River, the United States, and Mexico. *Policy Sci* 21:23–39.
16. Cayan DR, et al. (2010) Future dryness in the southwest US and the hydrology of the early 21st century drought. *Proc Natl Acad Sci USA* 107:21271–21276.
17. Woodhouse CA, Meko DM, MacDonald GM, Stahle DW, Cook ER (2010) A 1,200-year perspective of 21st century drought in southwestern North America. *Proc Natl Acad Sci USA* 107:21283–21288.
18. Seager R, et al. (2007) Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* 316:1181–1184.
19. Pierce DW, et al. (2008) Attribution of declining western US snowpack to human effects. *J Climate* 21:6425–6444.
20. Barnett TP, et al. (2008) Human-induced changes in the hydrology of the western United States. *Science* 319: 1080–1083.
21. Hidalgo HG, et al. (2009) Detection and attribution of streamflow timing changes to climate change in the western United States. *J Climate* 22:3838–3855.
22. Das T, et al. (2009) Structure and origins of trends in hydrological measures over the western United States. *J Hydrometeorol* 10:871–892.
23. The Water Sector Report of the National Assessment (2000) *The Impacts of Climatic Change and Variability on the Water Resources of the United States* (National Assessment, US Global Change Research Program, and Pacific Institute, Washington, DC, and Oakland, CA).
24. Allen CD (2007) Cross-scale interactions among forest dieback, fire, and erosion in northern New Mexico landscapes. *Ecosystems* 10:797–808.
25. Yuhas AN, Scuderi LA (2009) MODIS/NDVI detection of vegetation dieoff. MODIS- derived NDVI characterisation of drought-induced evergreen dieoff in western North America. *Geogr Res.* 47:34–45.
26. Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western U.S. forest wildfire activity. *Science* 313:940–943.
27. Westerling AL, Bryant BP (2008) Climate change and wildfire in California. *Climatic Change* 87:231–249.
28. National Research Council (2008) *Desalination: A National Perspective* (National Academies Press, Washington, DC), 298 pp.
29. Gleick PH (2003) Water use. *Annu Rev Env Resour* 28: 275–314.
30. Stonestrom DA, Harrill JR (2007) *Ground-Water Recharge in the Arid and Semiarid Southwestern United States—Climatic and Geologic Framework. Professional Paper 1703-A* (US Geological Survey, Reston, VA).
31. Cooley H, Christian-Smith J, Gleick PH (2008) More with less: The potential for agricultural conservation and efficiency in california. Research report of the Pacific Institute. Available at: http://www.pacinst.org/reports/more_with_less_delta/index.htm. Accessed September 21, 2010.
32. Gleick PH (2000) The changing water paradigm: A look at twenty-first century water resources development. *Water Int* 25:127–138.
33. US Geological Survey. *Estimated Use of Water in the United States, Various years. Circular 1344* (US Geological Survey, Reston, VA).
34. Cooley H, Hutchins-Cabibi T, Cohen M, Gleick PH, Heberger M (2007) Hidden oasis: Water conservation and efficiency in Las Vegas. Report of the Pacific Institute. Available at: http://www.pacinst.org/reports/las_vegas/index.htm. Accessed September 21, 2010.
35. Chesnutt TW, Fiske G, Pekelney D, Beecher J (2008) Water efficiency programs for integrated water management. *J Am Water Works Assoc* 100:132–141.
36. Kirshen P, Fennessey N (1995) *Potential Impacts of Climate Change on the Water Supply of the Boston Metropolitan Area. EPA 230-R-95-003* (US Environmental Protection Agency, Washington, DC).
37. Hamlet AH (2010) Assessing water resources adaptive capacity to climate change impacts in the Pacific Northwest region of North America. *Hydrol Earth Syst Sci* 7:4437–4471.
38. Miles EL, Elsner MM, Littell JS, Whitely Binder LC, Lettenmaier DP (2010) Assessing regional impacts and adaptation strategies for climate change: The Washington Climate Change Impacts Assessment as a case study. *Climatic Change*, 10.1007/s10584-010-9853-2.