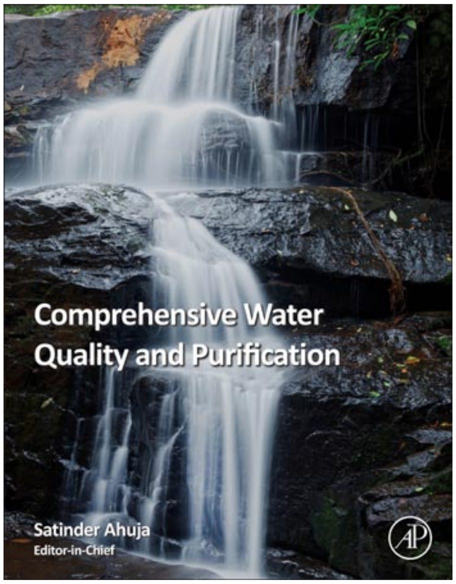

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1.2 Global Change and Water Availability and Quality: Challenges Ahead

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1.2.1 Introduction

The US is experiencing, without explicit intent or design, a national scale multiyear population, land use, and economic experiment that is creating major water resources challenges and potential conflicts for the twenty-first century. These challenges affect both the quantity and quality of water resources. Similar serious water resources challenges exist or are emerging in many other countries as well and are predicted to intensify in the coming decades, particularly with respect to global scale changes in population and economic development (Vörösmarty et al., 2000; Gleick, 2011). As competition for resources intensifies, the need for water resources information based on sustained, robust monitoring networks for tracking the quantity and quality of streamflow and groundwater has never been greater (Hirsch, 2011). The hydrological data from such networks are critically needed to inform the often contentious discussions among water resources stakeholders and to reduce uncertainty in the decision making of resource managers (Stakhiv, 2011). These data help mitigate current and potential conflict over water resources (Interagency Climate Change Adaptation Task Force, 2011) (*see* Chapters 1.3, 1.4, 4.8, 4.16, and 1.5).

In contrast to many popular media accounts regarding these conflicts, according to Barnaby (2009), nations have never gone to war over water resources. She notes, "Countries do not go to war over water, they solve their water shortages through trade and international agreements. Cooperation, in fact, is the dominant response to shared water resources." In spite of this, willingness of nations ultimately to cooperate on the use of the water resources that cross international borders, local, interstate, and international disagreements are a constant concern and derived from a number of factors, both new and old (Gleick, 2011; Stakhiv, 2011). Some of the emerging factors are described in this chapter, using examples mainly from the US. These are fundamental challenges that are likely to complicate water resources management for much of the twenty-first century in the US and abroad.

1.2.2 Population and Land-Use Change

Population in the US is expanding at two to three times the national growth rate in the nation's most water-scarce region, the southwestern US, where water stress is already great. During the period 1990–2000, Arizona population grew by 40% and population in Nevada by 66% (U.S. Census Bureau, 2001). Growth rates in these two states declined somewhat during the period 2000–10 to 25–35%, but remain high, considering that the national growth rate is 9.7% (U.S. Census Bureau, 2011). The 10 fastest growing metropolitan areas of the US during the 1990s were in Arizona, Florida, Idaho, Nevada, Texas, and Utah. This trend shifted somewhat in the 2000–10 decade, with the addition of North and South Carolina, Oregon, and Colorado to the top 10 list, and with Idaho dropping off. However, most of these rapidly growing states are in regions where water resources are limited by relatively dry climates or are subject to saltwater intrusion into coastal aquifers.

Many of these high-growth states are vulnerable to changes in water availability and quality. Modeling studies predict decreased streamflow in western midlatitude North America by the middle of this century and attribute this change to increased temperature and evapotranspiration (Milly et al., 2005; Karl et al., 2009; Overpeck and Udall, 2010). The Colorado river's average annual flow could decrease by 20% by 2050 (Overpeck and Udall, 2010). Runoff in the Arizona–Nevada region is predicted to decrease by 20–40% by the period 2041–60 compared to runoff measured during the period 1900–70 (**Figure 1**).

During the period 2000–05, land use in irrigated agriculture in the US decreased in the west (see **Figure 2**, for east/west division) and increased in the east, particularly in the southeastern states, where heightened competition for ground and surface water has urban, agricultural, and environmental interests at odds, and increasingly, in court (**Figure 3**). Total irrigated area decreased in the west by 4% and increased in the east by 5%, from 2000 to 2005 (Kenny et al., 2009). Among the eastern states, Arkansas, Mississippi, Missouri, and Florida had the largest withdrawals for irrigation (**Figure 2**).

Land use is changing in the upper Mississippi, Missouri, and Ohio rivers' watersheds in response to a number of factors, including production of biofuels, which has increased substantially in the past decade as evidenced by ethanol production and the construction of new biofuel refineries. A new US Government goal calls for 136 billion liters of ethanol per

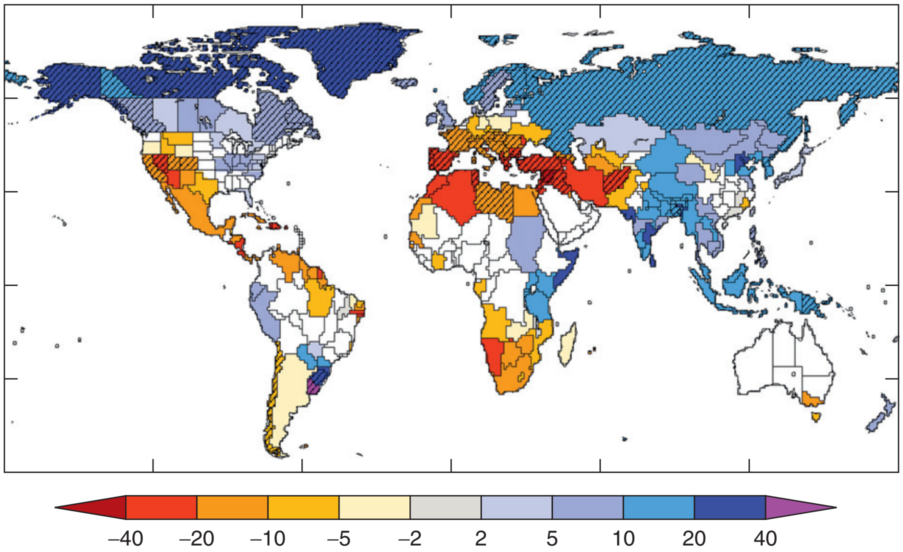


Figure 1 Model-projected changes in annual runoff, 2041–60. Percentage change relative to 1900–70 baseline. Any color indicates that >66% of models agree on sign of change; diagonal hatching indicates >90% agreement. Reproduced from Milly, P. C. D., Dunne, K. A. and Vecchia, A. V. (2005). Global pattern of trends in streamflow and water availability in a changing climate. *Nature* **438**, 347–350.

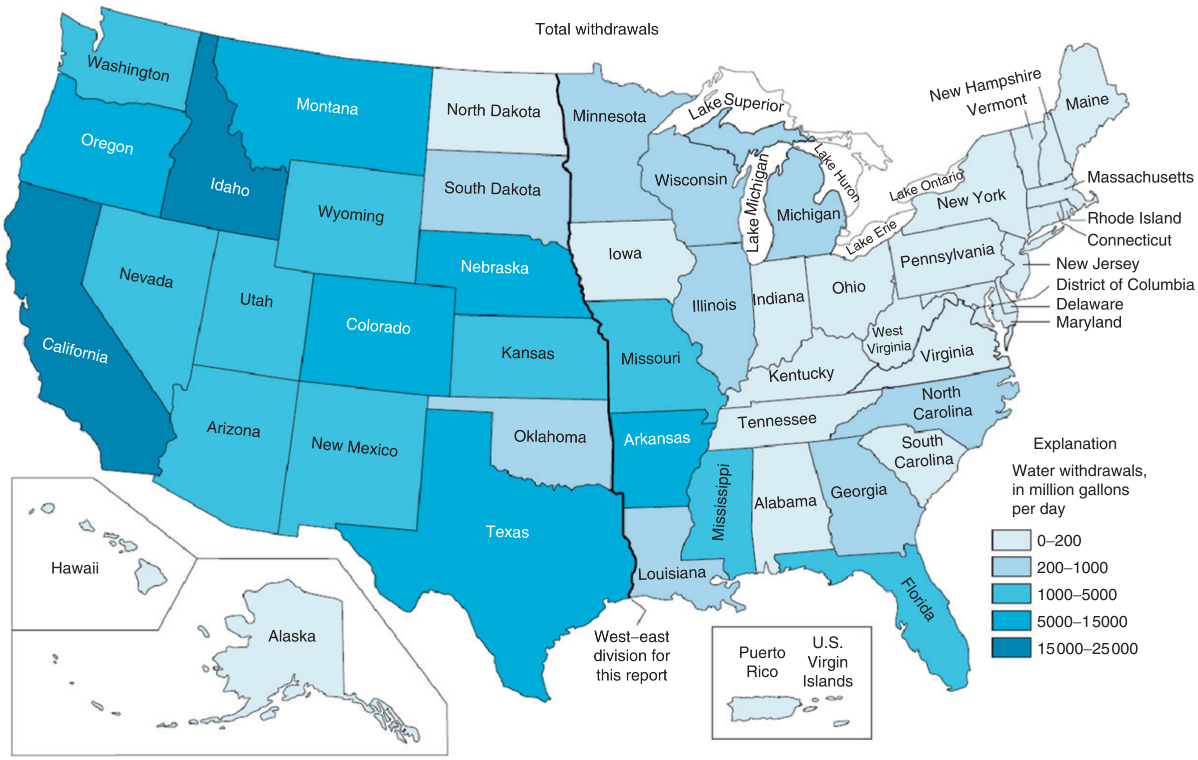


Figure 2 Map of the US, showing irrigation withdrawals by state, 2005. Reproduced from Kenny, J. F., Barber, N. L., Hutson, S. S., et al. (2009). Estimated use of water in the United States in 2005. *U.S. Geological Survey Circular 1344*, p. 52. Available at http://pubs.usgs.gov/circ/1344/ (accessed on 31 October 2011).

year by 2022; this is expected to result in increased corn production until alternative crops gain more use (NRC, 2008; USEPA, 2010). Increased land in agricultural production is expected to elevate already high levels of nutrients in runoff and water recharging aquifers in this region (Alexander et al., 2007).

1.2.3 Anthropogenic Substances and Water Supply

The consumption of pharmaceutical and personal care products (PPCPs) in the US is at historic high levels with PPCPs entering surface and groundwater, through sewage treatment

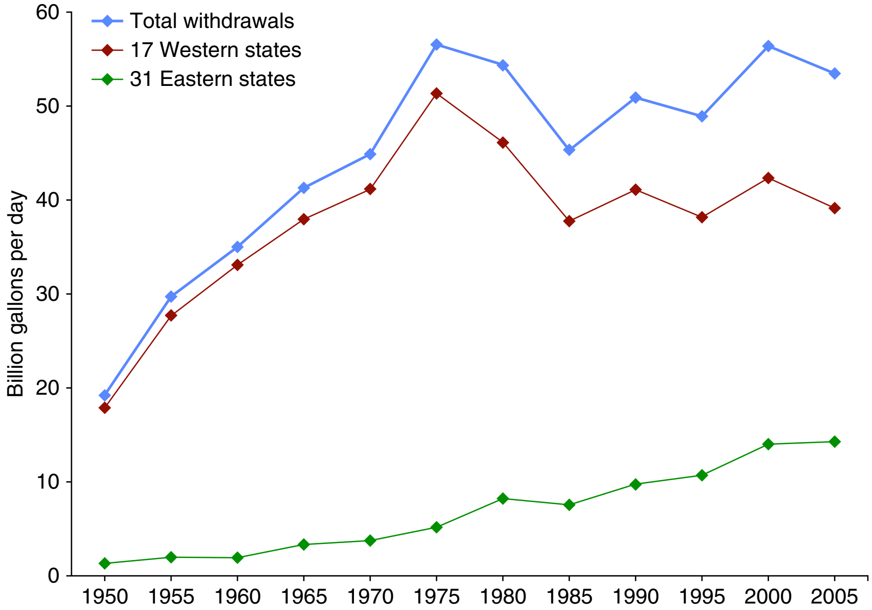


Figure 3 Groundwater withdrawals for irrigation, the US, 1950–2005, showing decline in the west and increase in the east. Reproduced from U.S. Geological Survey.

plants, individual septic systems, runoff from animal feedlots, and landfill leachate. According to the World Health Organization, the market share of the US alone for global pharmaceutical sales rose from 18% of the world total in 1976 to more than 52% in 2000 (WHO, 2004). In just a year, sales of pharmaceuticals in North America grew by 5.2% (from 2004 to 2005) and totaled $266 billions (Gray, 2006).

In the first national scale examination of emerging contaminants in streams of the US, water samples were collected from streams considered to be susceptible to contamination in 30 states during 1999 and 2000. A broad range of PPCPs were detected in residential, industrial, and agricultural wastewaters in mixtures at low concentrations. The compounds include human and veterinary drugs, natural and synthetic hormones, detergent metabolites, plasticizers, insecticides, and fire retardants. One or more of these chemicals were found in 80% of the streams sampled (Kolpin et al., 2002).

In a US Geological Survey (USGS) study by Focazio et al. (2008) of 25 untreated ground- and 49 surface-water drinking water sources serving populations ranging from one family to more than 8 million people, 63 of 100 targeted chemicals were detected in at least one water sample. The five most frequently detected targeted chemicals in surface water were: cholesterol (59%, natural sterol), metolachlor (53%, herbicide), cotinine (51%, nicotine metabolite), β-sitosterol (37%, natural plant sterol), and 1,7-dimethylxanthine (27%, caffeine metabolite); and in groundwater: tetrachloroethylene (24%, solvent), carbamazepine (20%, pharmaceutical), bisphenol-A (20%, plasticizer), 1,7-dimethylxanthine (16%, caffeine metabolite), and tris(2-chloroethyl) phosphate (12%, fire retardant).

These substances are known to have marked effects on aquatic species, particularly on fish reproduction function. Scientists yet neither know if effects on human health will emerge nor do they know if society will need to make large investments in water treatment systems, which were not designed to remove these substances (Jones et al., 2007). An additional complication is that these substances and others derived from human activities are more concentrated during periods of reduced streamflow associated with drought and reduced snowmelt runoff discussed in Section 1.2.5. Understanding and predicting low streamflow conditions are essential for regulatory agencies as they face increasingly complex management problems in the future (Eng et al., 2011).

1.2.4 Environmental Flows and Aquatic Ecosystem Needs

Environmental flows are those flows that sustain healthy ecosystems and the goods and services that humans derive from them. Largely because of the Endangered Species Act, first passed in 1973, decision makers are required to include fish and other aquatic species in negotiations over how much water to leave in the river, rather than, as in the past, how much water humans could remove from a river. Additionally, resource managers must pay attention to the quality of that water, including its temperature (Haak et al., 2010; Carlisle et al., 2011).

The combination of factors resulting from direct anthropogenic influences and climate change are a challenge for water- and wildlife-resource management, particularly in the western US (Overpeck and Udall, 2010). Twentieth century warming has already affected salmonid habitat, with unfavorable changes to thermal and hydrological properties of aquatic systems supporting coldwater fisheries (Haak et al., 2010). In their work on native trout and grayling in 11 western states, the authors note that climate model output indicates that these trends will continue and even accelerate until at least the middle of the twenty-first century. Haak et al. (2010) note that, drought is the most pervasive threat, with 40% or more of the historic range

for seven taxa at high risk. In contrast, population pressure and land-use change in Colorado have eliminated Greenback cutthroat trout from much of their former habitat, and most of the remaining populations occur in higher elevation streams and lakes (Haak et al., 2010). Drought is a relatively high risk factor for this fish; additionally, increasing summer temperatures and wildfires present higher risks within historic habitat in the South Platte Basin (Haak et al., 2010).

The need is great to better understand and manage the whole hydrograph and the influence of hydrological variability on aquatic ecosystems (Hirsch, 2011). Through various water management activities (withdrawals, storage, etc.), humans have trimmed the tails off the probability distribution of flows, mainly in larger streams and rivers. In order to more effectively manage these flow systems, water managers need to understand how to adjust the flow regime so that both human and ecological needs are met. The current environmental flow challenges have been described as:

- integrating physical and biological responses at the scale of river ecosystems to understand critical needs for streamflow and to link and predict ecological responses to streamflow changes;
- evaluating the ecological outcomes of environmental flow management to increase their efficacy and precision by hypothesis testing and monitoring; and
- translating scientific understanding about rivers into operational guidance for water managers and assessing ecological potential given water management constraints (Konrad, 2011; Konrad et al., 2008).

The dispute between Georgia, Florida, and Alabama over flows in the Apalachicola–Chattahoochee–Flint river system and the ecologically important estuary downstream, the Apalachicola Bay, is an example of a recent environmental flows conflict that developed in the southeastern US. Approximately 10% of all oysters consumed in the US are harvested from Apalachicola Bay (Ruhl, 2005). The conflict arises between interests supporting ecological productivity in the Bay region, upstream hydropower production, cooling of downstream power plants, irrigated agriculture, and public water supplies for the Atlanta metropolitan area. A recent multiyear drought exacerbated the conflict, and although the drought was partially mitigated by above-average rainfall in the late 2009, the regional conflict and drought continue as of this writing (2012).

1.2.5 Effects of Changes in Streamflow Timing and Precipitation Type

A critical role for the USGS and other federal agencies in climate change science is to measure and describe hydrological and meteorological changes that are currently underway (Lins et al., 2010) and place them in perspective with changes that have occurred in the past due to natural variability, as documented in long-term hydrological and meteorological instrumental records, historical documents, ice cores, tree rings, and lake sediment cores (Myers et al., 2007). Precipitation and streamflow patterns have been changing during the past several decades and are predicted to continue to change, with western midlatitude North America generally drier (Milly et al., 2005; Overpeck and Udall, 2010) (**Figure 1**). This prediction of regional drying is based on expected increased temperature and associated increased evapotranspiration. Additionally, reduced streamflow means less dilution of naturally occurring and anthropogenic substances in surface water, resulting in negative effects on water quality. In contrast, the last several decades have been a period of increasingly wetter conditions in eastern areas of North America and climate model projections call for generally wetter conditions, in part because a warmer atmosphere can hold more moisture and release more precipitation (IPCC, 2007).

Hydrologists have documented trends in more rain and less snow in the mountains of the western US (Knowles et al., 2006; Pederson et al., 2011a, b) (**Figure 4**). This has major implications for water supply and storage as well as groundwater recharge (Barnett et al., 2008). Hydrologists have documented earlier snowmelt peak spring runoff in northeastern and northwestern states and western montane regions (Huntington et al., 2004; Hodgkins and Dudley, 2006; Knowles et al., 2006; Mastin et al., 2011). According to Stewart et al. (2004), peak snowmelt runoff is now approximately 2 weeks earlier than observed during the period 1948–2000 in many western rivers and is predicted to be 30–40 days earlier as the twenty-first century progresses. A region-wide trend in spring advancement of snowmelt runoff of approximately −1.5 days per decade from 1950 to 2005 has been documented for western North America (Pederson et al., 2011b).

Tree-ring records provide a long-term perspective of regional climate and indicate that multidecadal droughts have occurred in the southwest within the past 400 years (Gray et al., 2003) followed by wetter periods. Pederson et al. (2011a) studied western North American snowpack declines using snowpack reconstructions from 66 tree-ring chronologies in headwater basins of the Colorado, Columbia, and Missouri rivers. These three basins are the primary water source for more than 70 million people, and 60–80% of their water originates as snowpack. The authors note that "over the past millennium, late 20th century snowpack reductions are almost unprecedented in magnitude across the northern Rocky Mountains and in their north-south synchrony across the cordillera." They attribute the snowpack declines to springtime warming resulting from positive reinforcement of anthropogenic warming by decadal variability. They conclude that the increasing role of warming on large-scale snowpack variability and trends will have a fundamental impact on streamflow and water supplies across the western US (Pederson et al., 2011a).

Decreased summer runoff affects water quality and supply for multiple uses. In addition to the reduced volume of streamflow during warm summer months, less water results in elevated stream temperature, which affects cooling for thermoelectric and some solar power generating facilities and the associated aquatic ecosystems (Hurd et al., 2004). These authors estimated a substantial increase in costs for thermoelectric cooling and consequent reduction in power generation under climate-change scenarios with increased temperature.

Much of the public assumes monotonic and regionally generalized patterns of climate change, but in reality, water resources managers are faced with hydrological trends that vary regionally and temporally. Although decreases in

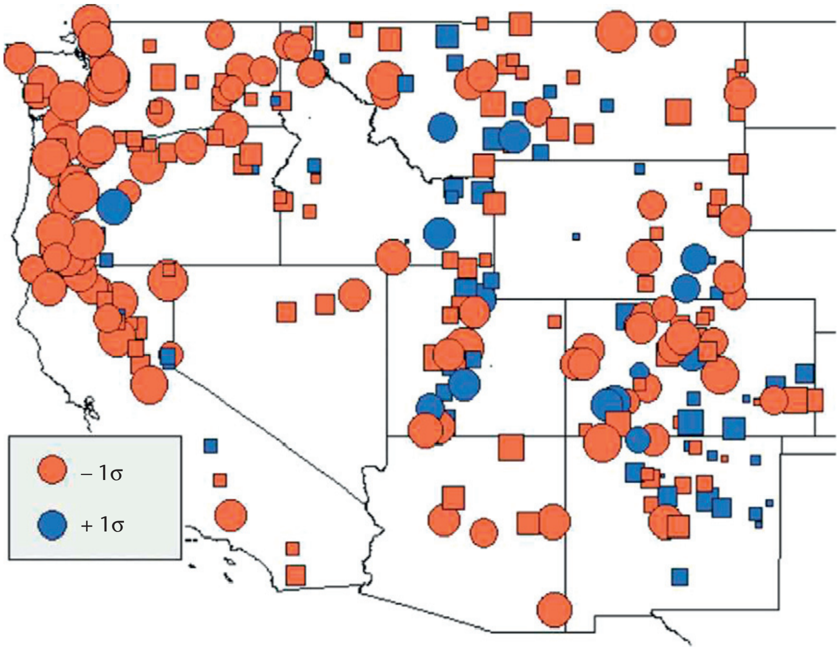


Figure 4 Map of western US showing sites of changing fraction of winter (November–March) rain to snow. Red indicates more rain and blue indicates more snow, 1949–2004. Symbol radius is proportional to study period changes, measured in standard deviations of detrended time series; circles indicate high trend significance ($p < 0.05$), and squares indicate lower trend significance. Reproduced from Knowles, N., Dettinger, M. D. and Cayan, D. R. (2006). Trends in snowfall versus rainfall in the western United States. *Journal of Climate* **18**, 4545–4559, with permission from American Meteorological Society.

streamflow are anticipated in western states, wetter conditions recently have occurred in the midcontinent. In eastern North Dakota, for example, water levels in lakes have recently been at the highest level in 160 years (Vecchia, 2008), consistent with a pattern of episodic wetter periods over the past 2000 years. Increases in streamflow were reported in the Great Plains, where on average, a 12% increase in annual precipitation led to a 64% increase in streamflow in 10 watersheds in Nebraska, Kansas, and Oklahoma (Garbrecht et al., 2004).

Water resources managers are challenged by the long-term complexity of hydrological trends (Lins et al., 2010). USGS streamflow data from the Red river of the North at Grand Forks, ND, USA, for the period 1882–2009, provides an example of this. According to Lins et al. (2010), analysis of the record for the period 1930–2009 indicates a substantial upward trend in annual peak flood discharges that appears to continue to the present. But, if the entire period of record is assessed, it can be seen that annual floods arise from at least two substantially different statistical populations. There are very large annual peak discharges from 1882 to about 1900 and again after about 1942, and much smaller peaks from about 1900 to 1942. In considering the entire period of record, it becomes apparent that very large floods were common well before the onset of large increases in greenhouse gases or extensive land modifications (Lins et al., 2010).

1.2.6 Sea-Level Rise and Water Supply

Sea-level rise presents challenges for freshwater extraction from coastal aquifers, which can be compromised by increased saline intrusion. Furthermore, although sea-level rise can increase saltwater intrusion into coastal surface and groundwater (when withdrawals increase or recharge decreases; see Chang et al., 2011), saltwater movement also results from changes in precipitation, runoff, and recharge that may occur within coastal watersheds (Barlow, 2003; Werner and Simmons, 2009). The most immediate threat to water supplies in coastal areas, however, is not from sea-level rise, but rather the current high rate of groundwater use in these regions. For example, withdrawal of groundwater for water supply in US Atlantic coastal counties in 1995 totaled 29 billion liters per day (Barlow, 2003). Barlow describes a number of case studies, from Maine to Florida, in which proximity of coastal aquifers to saltwater has resulted in water-management challenges with respect to groundwater sustainability. These challenges are primarily those of saltwater intrusion into freshwater aquifers and changes in the amount and quality of fresh groundwater discharge to coastal saltwater ecosystems.

A related problem faces users of 'run-of-the-river' water-supply intakes that are threatened as salt fronts migrate upstream because of higher sea level. As early as 1986, this problem was acknowledged when the Delaware river Basin Commission and US Environmental Protection Agency (USEPA) jointly published a report (Hull and Titus, 1986) noting that sea-level rise could substantially increase the salinity of the Delaware estuary in the twenty-first century, roughly equivalent to a repeat of the 1960s drought, which allowed the salt front to migrate upstream where it threatened water intakes. They noted that accelerated sea-level rise could cause excessive salinity concentrations at Philadelphia's public supply intake if no countermeasures were taken. For a 73 cm

sea-level rise, sodium concentrations would exceed 50 ppm (the New Jersey drinking water standard) during 15% of the tidal cycles during a recurrence of the 1960s drought. Furthermore, accelerated sea-level rise could threaten New Jersey aquifers recharged by the Delaware river (Hull and Titus, 1986). Later work by Ayers et al. (1994) arrived not only at similar conclusions but also noted that increased Delaware river discharge could counteract the effect.

Finally, another aspect of the relation between sea-level rise and water supply is that groundwater depletion has been shown to be a small but nontrivial and increasing factor in the global sea-level rise (Milly et al., 2010; Konikow, 2011). According to Konikow (2011), estimated global groundwater depletion during 1900–2008 totals ~4500 km^3, equivalent to a sea-level rise of 12.6 mm (>6% of the total). Konikow further states that

> the rate of groundwater depletion has increased markedly since about 1950, with maximum rates occurring during the most recent period (2000–2008), when it averaged ~145 km^3/yr (equivalent to 0.40 mm/yr of sea-level rise, or 13% of the reported rate of 3.1 mm/yr during this recent period).

1.2.7 What Are We Likely to See in the Twenty-First Century?

The water resources challenges illustrated above have placed federal, state, and local water resources managers in the US on an aggressive path toward increased efficiency and conservation. These adaptive efforts will likely expand substantially in the coming decades. A few examples are described below.

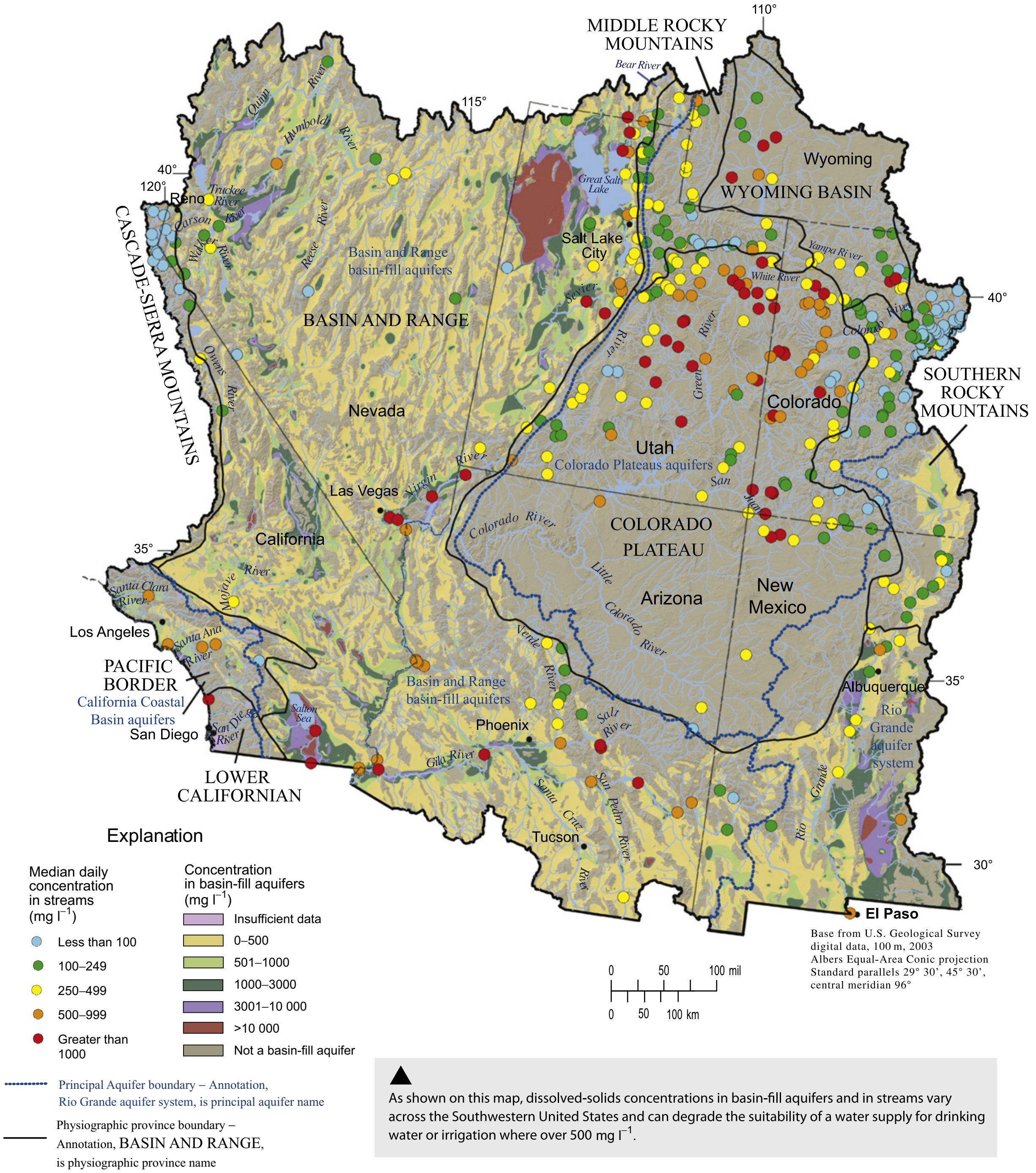
As US population growth continues, cities in water-stressed areas will likely expand already implemented policies to improve water-use efficiency and reduce consumption. The Las Vegas, Nevada, area has seen water consumption decrease by nearly 79.5 billion liters between 2002 and 2008, despite a population increase of 400 000 during that period (P. Mulroy, Southern Nevada Water Authority, oral communication, 2010). This reduced consumption has been achieved through a combination of pricing incentives such as tiered-rate structures that charge higher rates as water use increases, a rebate program that offers $1.50 for the first 465 m^2 of lawn removed up to $300 000, and subjecting golf courses to mandatory annual water budgets of 19.2 million liters per irrigated hectare. Significant challenges remain to be solved in this water-scarce region, as urban water needs to compete with those of rural domestic water supply, irrigated agriculture, and environmental requirements for sustaining federally listed and water-dependent endemic species (Deacon et al., 2007). In Arizona, state tax incentives for gray water and rainwater harvesting systems administered by the State of Arizona Department of Revenue (2011) offer 25% of costs up to $1000 for residential properties. The city of Tucson, Arizona, where annual rainfall measures 305 mm, initiated a xeriscape landscaping code that applies to new multifamily, commercial, and industrial development, with a goal of conserving water by using xeriscape principles in landscape design. In some areas, these types of policies can be controversial, for example, prior appropriation water law in Colorado prohibits the harvesting of rainwater.

Water used for irrigation has leveled off in the US since 1985 (Kenny et al., 2009) and is likely to decrease further because of a combination of factors including:

- increased costs to lift groundwater from greater depths where aquifers are being depleted;
- increased market value of water rights resulting in metropolitan area water agencies buying water rights from irrigators;
- increased energy prices;
- decreased well yields resulting from decreases in the saturated thickness of aquifers (because of drawdown);
- advances in irrigation technology such as lower pressure sprinkler systems to improve application of irrigation water, and precise monitoring of soil moisture using new remote sensing-based techniques, such as Landsat data (Tasumi and Allen, 2007); and finally
- increased competition for surface water, particularly in western states where most surface water is fully appropriated at present.

Because of these stressors on irrigation, continued improvement in irrigation practices is likely to be seen. An example from the southwestern US is described by Anning et al. (2010) in a study based on more than 30 years of USGS and other salinity data in streams and groundwater in the southwest US (**Figure 5**). Salinity levels in streams and groundwater in parts of Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming decreased from 1989 through 2003 at all sites downstream from salinity-control projects, and the decreases were greater than decreases upstream from projects. Changes in land and water use, reservoir management, transbasin exports, and implementation of salinity-control projects, including using low water-use irrigation systems and redirecting saline water away from streams, improved water quality in the Colorado river basin by lowering salinity. Salinity-control projects have been implemented since the mid-1970s by the Bureau of Reclamation, US Department of Agriculture, and the Bureau of Land Management, to control the salinity of water delivered to Mexico, as per the 1974 Colorado River Basin Salinity Control Act.

Present day concerns regarding drinking water quality could increase if more scientific information about adverse effects of pharmaceuticals and other anthropogenic substances in water supply are documented (Barber et al., 2011; Vajdaa et al., 2011). The degree to which water suppliers will be required to modify sewage and water treatment facilities in response to these potential concerns is difficult to predict. Although the effects of these substances on aquatic fauna have been described in numerous studies (Barber et al., 2006), the effects on human health have not yet been well quantified. The USEPA's Unregulated Contaminant Monitoring Rule (UCMR) requires that public water suppliers monitor selected unregulated contaminants in finished drinking water supplies (USEPA, 1999). At present, however, the UCMR contaminants do not include the organic wastewater contaminants targeted by many studies; as such, the national-scale occurrence data needed by regulators to make informed decisions on whether or not to set drinking water standards are minimal or nonexistent for many of these substances in the US (Focazio et al., 2008).



As shown on this map, dissolved-solids concentrations in basin-fill aquifers and in streams vary across the Southwestern United States and can degrade the suitability of a water supply for drinking water or irrigation where over 500 mg l^{-1}.

Figure 5 Map of southwestern US, showing dissolved solids concentrations in rivers and aquifers. Reproduced from Anning, D. W. (2008). Dissolved solids in basin-fill aquifers and streams in the southwestern United States – Executive summary. *U.S. Geological Survey Fact Sheet 2008-3076*. Available at http://pubs.usgs.gov/fs/2008/3076/ (accessed on 12 June 2012).

As the temporal and spatial patterns of precipitation distribution continue to change in North America and elsewhere, water resources managers will be further challenged in their already difficult decision making for allocation of water supplies. For example, Barnett and Pierce (2008) have estimated that there is a 50% chance that Lake Mead, a key source of water for the southwestern US, will be dry by 2021 if the climate warms as predicted and if regional water consumption is not reduced. Barnett and Pierce (2009) stated that

> scheduled future water deliveries from the Colorado River are not sustainable. However, the ability of the system to mitigate droughts can be maintained if the various users of the river find a way to reduce average deliveries.

Other changes, already documented, such as more rain and less snow in western North America, will increase the cost of water as managers will be required to develop alternatives to the 'free' storage of water in winter snowpack. These alternatives could include more use of costly approaches and methods already in place at small scales, such as aquifer storage and recovery, desalination, and increases in reservoir storage capacity.

If energy costs can be mitigated, the use of desalination is likely to become more widespread by water utilities in the US and abroad, as they face the simultaneous reduction in both the quantity and quality of available water. The USGS is currently developing plans to assess brackish groundwater as a potential water supply source (U.S. Geological Survey, 2012). Abroad, the water-limited city state of Singapore has adapted to this challenge by importing water, through land reclamation, and through a combination of rainfall storage, desalination, and use of sophisticated treatment of wastewater to a drinking water standard, distributing 'new water' to consumers (Tortajada, 2006).

Sea-level rise during the twentieth century was 3–4 mm yr^{-1} in the mid-Atlantic region of the US (Titus et al., 2009). This rate of rise, likely to continue or accelerate, will challenge water resources managers in coastal regions as groundwater aquifers are degraded by increased chloride levels in locations where withdrawals increase or recharge decreases. Adaptation will include closure of well fields; desalination of brackish groundwater; artificial recharge of coastal aquifers using gray water and using surplus water during wet periods; and optimization of groundwater pumping to prevent or minimize upconing or lateral migration of saline groundwater.

Finally, the gradual rise in sea level notwithstanding, society is faced with a choice as to where and at what rates groundwater is extracted in close proximity to saline water (whether marine or geological). The issues that these communities face will be virtually the same with or without sea-level rise. Conservation, good management, development of conjunctive use schemes, and regional cooperation are all key factors to managing these issues. At present, these solutions are more cost effective than most technological alternatives such as desalination.

1.2.8 Conclusions

Water resources quantity and quality challenges that are faced in this century arise from a combination of local and national water management activities; from climate-change impacts, such as rising temperatures and changes in precipitation patterns, that are already on us; and from population, land use and economic change. These are international challenges that are frequently characterized in the popular media as flashpoints for strife (Starr, 1991). However, as noted in the introduction, according to Barnaby (2009) nations have never gone to war over water resources: "Countries do not go to war over water, they solve their water shortages through trade and international agreements." And further, "Water management will need to adapt. But the mechanisms of trade, international agreements and economic development that currently ease water shortages will persist." As such, it is incumbent on the government at all levels to proactively engage stakeholders and the scientific and engineering community to help mitigate water resources challenges and to assure equity in resource distribution, thereby diminishing conflict. A critical need will be scientific understanding supported by sustained, robust monitoring networks for tracking the quantity and quality of streamflow and groundwater. The hydrological data and the continuing improvement in prediction capabilities derived from such networks will inform discussions among water resources stakeholders and reduce uncertainty in the decision making of resource managers. These data also play a critical role in helping scientists evaluate the ability of predictive water and climate models to forecast the future, by using the past data and comparing them to the outputs of these models operated in hindcast mode. If models are to be relied on, they must have demonstrable skill.

Milly et al. (2008) noted that systems for management of water throughout the developed world have been designed and operated under the assumption of stationarity, which assumes that natural systems fluctuate within an unchanging envelope of variability. However, these authors argue that climate change undermines this basic assumption that historically has facilitated the management of water supplies, demands, and risks. Thus, it is useful to place current climate change in context with past climate variability evident from long-term streamflow and precipitation records, and over larger time scales, the record in ice cores, tree rings, and lake sediment cores and other natural records. It should be noted that in the past, water resources managers did not rate climatic change among their top planning and operational concerns, because the magnitude of effects due to changes in climate on water resources was small relative to changes in variables such as population, technology, economics, and environmental regulation (Lins and Stakhiv, 1998). This approach was not unreasonable, given, for example, that reservoir-design criteria incorporate large buffering capacity for extreme meteorological and hydrological events. Climate and land-use change have, however, seriously complicated this approach.

In the US, federal agencies with a role in water resources have recognized that climate change is one of a number of important challenges for the planning and management of water resources and flood hazards (Brekke et al., 2009; Interagency Climate Change Adaptation Task Force, 2011). Scientists and managers in these agencies and in the larger scientific community have acknowledged that there remains a great deal of uncertainty about the exact character of those challenges and changes that will take place in the coming decades. This uncertainty is not a reason to take a 'wait and see' approach. Water planners and managers will be required to act in a manner that will be resilient to the types of changes that may happen and to be responsive to the changes as they become better observed and predicted in the future. The science supporting water resources management will be most effective if it can accurately describe the changes that are taking place, and update the hydrological statistics that are central to the planning, design, and operations of systems.

Acknowledgments

The work of many USGS scientists as well as others in the science community was used in this brief summary of water resources challenges. Robert M. Hirsch provided inspiration and insightful views that were a substantial contribution to this chapter. Jerad D. Bales, James W. LaBaugh, Robert M. Hirsch and Harry F. Lins are thanked for helpful review comments that improved this manuscript.

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