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GLOBAL CHANGE AND WATER RESOURCES IN THE NEXT 100 YEARS

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ABSTRACT. The economic, political, and scientific decision-making entities of U.S. society are in the midst of a continental-scale, multi-year experiment in the United States, in which we have not defined our testable hypotheses or set the duration and scope of the experiment, which poses major water-resources challenges for the 21st century. What are we doing? We are expanding population at three times the national growth rate in our most water-scarce region, the southwestern United States, where water stress is already great and modeling predicts decreased streamflow by the middle of this century. We are expanding irrigated agriculture from the west into the east, particularly to the southeastern states, where increased competition for ground and surface water has urban, agricultural, and environmental interests at odds, and increasingly, in court. We are expanding our consumption of pharmaceutical and personal care products to historic high levels and disposing them in surface and groundwater, through sewage treatment plants and individual septic systems. These substances are now detectable at very low concentrations and scientists have documented substantial effects on aquatic species, particularly on fish reproduction function. These are a few examples of our national-scale experiment.

In addition to these water resources challenges, over which we have some control, precipitation and streamflow patterns have been changing, and are predicted to change in coming decades, with western mid-latitude North America generally drier. Based on the instrumented record, hydrologists have already documented trends in more rain and less snow in western mountains. Hydrologists have documented earlier snowmelt peak spring runoff in northeastern and northwestern states, and western montane regions. Peak runoff is now about 2 weeks earlier than it was in the first half of the 20th century.

Decision makers are now required to include fish and other aquatic species in negotiation 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, decision makers must pay attention to the quality of that water, including its temperature.

Sea level rise presents challenges for fresh water extraction from coastal aquifers as they are compromised by increased saline intrusion. A related problem faces users of 'run-of-the-river' water-supply intakes that are threatened by a salt front that migrates further upstream because of higher sea level.

Global change and water resources challenges that we face this century include a combination of local and national management problems and evolving changes in climate that are already upon us. This set of challenges will continue and likely intensify as the non-climatic and climatic factors (such as predicted rising temperature and changes in the distribution of precipitation in time and space) continue to develop.

KEY TERMS: global change; water resources; water supply; streamflow; precipitation; sea level

INTRODUCTION

The United States is experiencing, without explicit intent or design, a national-scale, multi-year population, land use, and economic experiment which poses major water-resources challenges and potential conflicts for the 21st century. Similar serious water-resources challenges exist or are emerging in many other countries as well and are predicted to intensify in the coming 25 years, particularly with respect to global-scale changes in population and economic development (Vörösmarty et al., 2000). 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. The hydrologic data from such networks informs the often contentious discussions among water-resources stakeholders and reduces uncertainty in the decision-making of resource managers. These data help mitigate current and potential conflict over water resources.

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, inter-state, and international disagreements are a constant concern and derive from a number of factors, both new and old. Some of the emerging factors are described below, using examples mainly from the United States. These are fundamental challenges that are likely to complicate water-resources management for much of the 21st century in the U.S. and abroad.

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POPULATION AND LAND USE CHANGE

The U.S. is expanding population at three times the national growth rate in our most water-scarce region, the southwestern United States, 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). The 10 fastest growing metropolitan areas of the U.S. during this same period were all in Arizona, Florida, Idaho, Nevada, Texas, and Utah. With the exception of Florida, all are in regions where water resources are highly limited by relatively dry climates. Modeling studies predict decreased streamflow in mid-latitude North America by the middle of this century and attribute this change to increased temperature and evapotranspiration (Milly et al. 2005). Runoff in the Arizona-Nevada region is predicted to decrease by 20-40% by the period 2041-2060, compared to runoff measured during the period 1900-1970 (Figure 1).

Irrigated agriculture is expanding from the west into the east, particularly to the southeastern states, where increased competition for ground and surface water has urban, agricultural, and environmental interests at odds, and increasingly, in court (Figure 2). 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 and Florida had the largest withdrawals for irrigation.

Land use is changing in upper Mississippi River and Ohio River watersheds of the U.S. where production of biofuels has grown substantially in the past decade. 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). A new U.S. government goal calls for 36 billion gallons (136 billion liters) per year by 2022; this is expected to result in increased corn production until alternative crops gain more use (NRC, 2008; USEPA, 2010).

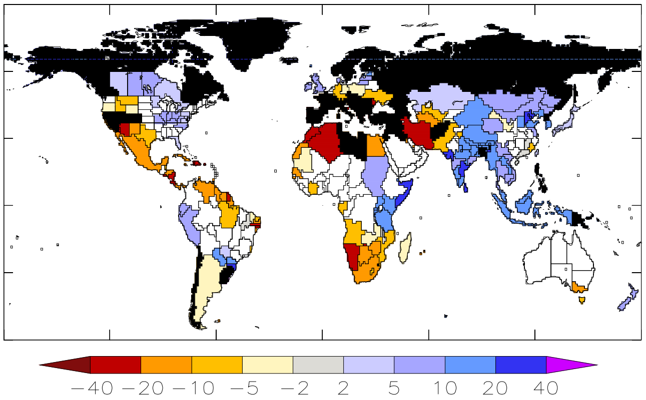

Figure 1. Model-projected changes in annual runoff, 2041-2060. Percentage change relative to 1900-1970 baseline. Any color indicates that >66% of models agree on sign of change; diagonal hatching indicates >90% agreement. Source: Milly et al. (2005).

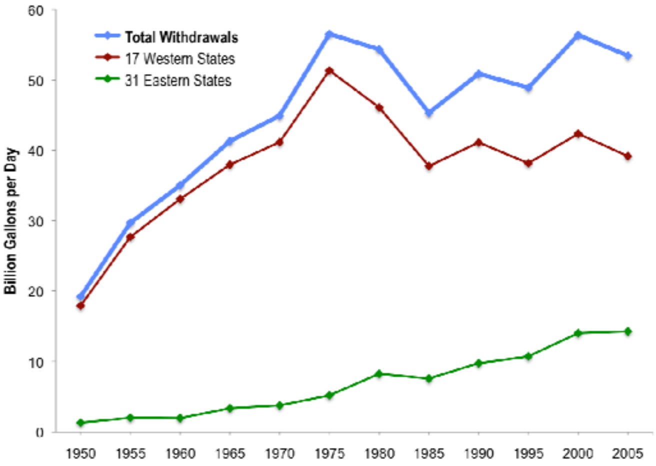

Figure 2. Groundwater withdrawals for irrigation, United States, 1950-2005, showing decline in the west and increase in the east. Source: Kenny et al. (2009).

ANTHROPOGENIC SUBSTANCES AND WATER SUPPLY

U.S. consumption of pharmaceutical and personal care products is at historic high levels and they are being disposed into surface and groundwater, through sewage treatment plants and individual septic systems. According to the World Health Organization, the market share of the U.S. alone for global pharmaceutical sales and consumption rose from 18 % of the world total in 1976 to over 52% in 2000 (WHO, 2004).

In the first national-scale examination of emerging contaminants in streams of the U.S., water samples were collected from streams considered to be susceptible to contamination in 30 states during 1999 and 2000. A broad range of chemicals was detected in residential, industrial, and agricultural wastewaters in mixtures at low concentrations. The chemicals 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 U.S. Geological Survey (USGS) study of 25 ground- and 49 surface-water sources, prior to treatment, of drinking water serving populations ranging from one family to over 8 million people, 63 of 100 targeted chemicals were detected in at least one water sample (Focazio et al., 2008). The five most frequently detected chemicals targeted 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 ground water: tetrachloroethylene (24%, solvent), carbamazepine (20%, pharmaceutical), bisphenol-A (20%, plasticizer), 1,7-dimethylxanthine (16%, caffeine metabolite), and tri (2-chloroethyl) phosphate (12%, fire retardant).

These substances are known to have marked effects on aquatic species, particularly on fish reproduction function. Scientists do not yet know what effects on human health may emerge, nor do they know if society needs to make large investments in water treatment systems, which were not designed to remove these substances.

ENVIRONMENTAL FLOWS AND AQUATIC ECOSYSTEM NEEDS

Environmental flows are defined as the flow of water in a natural river or lake that sustains healthy ecosystems and the goods and services that humans derive from them. Decision makers are now required to include fish and other aquatic species in negotiation 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. Furthermore, we must now better understand and manage the whole hydrograph and the influence of hydrologic variability on aquatic ecosystems. Humans have trimmed the tails off the probability distribution of flows. Water managers need to understand how to put the tails back on but cannot do that without improved understanding of aquatic ecosystems.

The current environmental flow challenges have been described as: linking streamflow to ecological responses; integrating physical and biological responses at the scale of river ecosystems to understand critical needs for streamflow and to 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; translating scientific understanding about rivers into operational guidance for water managers; and assessing ecological potential given water management constraints (C. Konrad, USGS, written communication, 2009; Konrad et al. 2008).

An example of a recent environmental-flows conflict that developed in the southeastern U.S. is the dispute between Georgia, Florida, and Alabama over the Apalachicola-Chattahoochee-Flint River Basin and an ecologically important estuary, the Apalachicola Bay. About 10 percent of all oysters consumed in the United States are harvested from Apalachicola Bay (Ruhl, 2005). The conflict is between interests supporting ecological productivity in the Bay region, upstream hydropower production and cooling, agriculture, and city of Atlanta domestic supply. A recent multi-year drought exacerbated the conflict, and although the drought was mitigated by above average rainfall in late 2009, the regional conflict continues as of this writing.

EFFECTS OF CHANGES IN STREAMFLOW TIMING AND PRECIPITATION TYPE

Precipitation and streamflow patterns have been changing during the past several decades and are predicted to continue to change in coming decades, with western mid-latitude North America generally drier (Milly et al., 2005) (Figure 1). This regional drying prediction is based on expected increased temperature and associated increase in evapotranspiration. A critical role for the USGS (and other science agencies) in climate change science is to measure and describe the 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 ice cores, tree rings, and lake sediment cores (Myers et al., 2007). Hydrologists have already documented trends in more rain and less snow in western mountains (Figure 3). This has large implications for water supply and storage, and groundwater recharge (Barnett et al., 2008). Hydrologists have documented earlier snowmelt peak spring runoff in northeastern and northwestern states, and western montane regions (Hodgkins and Dudley, 2006; Knowles et al., 2006). Peak snowmelt runoff is now about 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 21st century progresses (Stewart et al., 2006). Tree ring records provide a longer-term understanding of regional climate and indicate that multi-decadal droughts have occurred in the southwest within the past 400 years (Gray et al., 2003) followed by wetter periods.

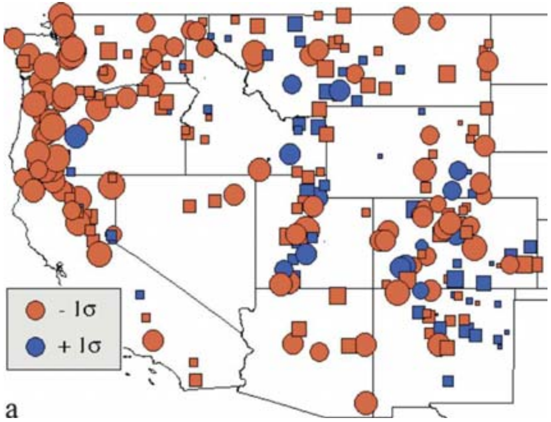

Figure 3. Map of western United States showing sites of changing fraction of winter (Nov–Mar) rain to snow. Red indicates more rain and blue indicates more snow, 1949–2004. Symbol radius is proportional to study period changes, measured in standard deviations of detrended time series; circles indicate high trend significance (*p* _ 0.05), and squares indicate lower trend significance. Source: Knowles et al. (2006).

Decreased summer runoff affects water supply for multiple uses. In addition to the reduced volume of streamflow during warm summer months, less water results in elevated stream temperature, which also effects on cooling of power generating facilities and on aquatic ecosystem needs (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.

Water-resources managers are faced with hydrologic trends that vary regionally. While decreases in streamflow are anticipated in western states, wetter conditions have occurred in mid-continent. In eastern North Dakota, for example, water levels in lakes are at the highest level in 160 years (Vecchia, 2008) consistent with a pattern of episodic wetter periods over the past 2000 years.

SEA LEVEL RISE AND WATER SUPPLY

Sea level rise presents challenges for fresh water extraction from coastal aquifers as they are compromised by increased saline intrusion. It should be further noted that although sea-level rise would increase saltwater intrusion into coastal surface and groundwater, landward saltwater movement also depends on changes in precipitation, runoff, and recharge that may occur within coastal watersheds (Barlow, 2003). 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 U.S. Atlantic coastal counties in 1995 amounted to 7.7 billion gallons/day (29 billion L/day) (Barlow, 2003). Barlow describes a number of cases 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 U.S. 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 21st century, roughly equivalent to a repeat of the 1960s drought, which allowed the salt front to migrate upstream where it threatened water intakes. They note that accelerated sea level rise could cause excessive salinity concentrations at Philadelphia's public supply intake if no countermeasures were taken. For a 2.4-ft (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 the New Jersey aquifers recharged by the Delaware River (Hull and Titus, 1986).

WHAT ARE WE LIKELY TO SEE IN THE 21ST CENTURY?

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

As U.S. population growth continues, cities in water stressed areas will continue to build upon already implemented policies to improve water-use efficiency and reduce consumption. The Las Vegas, Nevada, area has seen water consumption decrease by nearly 21 billion gallons between 2002 and 2008, despite a population increase of 400,000 during that period (P. Mulroy, Southern Nevada Water Authority, oral commun., 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 5,000 square feet (465 square meters) of lawn removed up to $300,000; subjecting golf courses to mandatory annual water budgets of 6.3 acre feet of water per irrigated acre (19.2 M liters per hectare). In Arizona, state tax incentives for gray water and rainwater harvesting systems administered by the State of Arizona Department of Revenue offer 25% of costs up to $1,000 for residential properties. The city of Tucson, Arizona, where annual rainfall measures 12 in. (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 principals in landscape design.

Water used for irrigation has leveled off in the U.S. since 1985 (Kenny et al., 2009) and is likely to decrease further because of a combination of factors: increased costs to lift groundwater from greater depths where aquifers are being depleted; increased charges for water in response to market forces; increased energy prices; decreased well yields resulting from decreased groundwater recharge; changes in irrigation technology; and increased competition for surface water, particularly in western states where most surface water is fully appropriated at present.

Present-day concerns regarding drinking-water quality will increase as more scientific information about pharmaceuticals and other anthropogenic substances in water supply is collected and published. The degree to which water suppliers will be forced to modify sewage and water treatment facilities in response to these concerns is difficult to predict. Although the effects of these substances on aquatic fauna have been documented 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 is minimal or nonexistent for many of these substances in the U.S. (Focazio et al., 2008).

As the temporal and spatial patterns of precipitation distribution change in North America and elsewhere, water-resources managers will be further challenged in their already difficult allocation of water supply. 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 U.S., will be dry by 2021 if the climate changes as predicted and regional water consumption are not reduced. 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 will include more use of costly approaches and methods already in place at small scales, such as aquifer storage and desalination.

Sea-level rise during the 20th century was 3 to 4 millimeters per year in the mid-Atlantic region of the U.S. (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. Adaptation will include closing of well fields; desalination of brackish groundwater; artificial recharge of coastal aquifers using surplus water during wet periods and gray water; and optimization of groundwater pumping to prevent or minimize upconing or lateral migration of saline groundwater.

CONCLUSIONS

Water resources challenges that we face this century include a combination of local and national management and climate-change problems that are already upon us, as well as emerging and future problems that are closely associated with population, land use and economic change as well as with rising temperature and changes in precipitation distribution in time and space resulting from climate change. These are international challenges, but, as noted above, 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 upon government at all levels to proactively engage stakeholders, and the scientific and engineering community to help mitigate water resources challenges and conflict and ultimately, to assure equity in resource distribution. A critical need will be scientific understanding supported by sustained, robust monitoring networks for tracking the quantity and quality of streamflow and groundwater. The hydrologic data from such networks will inform the often contentious discussions among water-resources stakeholders and reduce uncertainty in the decision-making of resource managers.

Milly et al., (2008) note that systems for management of water throughout the developed world have been designed and operated under the assumption of stationarity, which means 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 management of water supplies, demands, and risks. Thus, it is useful to place current climate change in context with past climate variability evident from 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 is not unreasonable, given that reservoir-design criteria incorporate large buffering capacity for extreme meteorological and hydrological events.

In the U.S., 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). 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.

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