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GLOBAL CHANGE AND WATER RESOURCES: WHERE ARE WE HEADED?

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The United States (U.S.) is in the midst of a continental scale, multi-year water resources experiment, in which society has not defined testable hypotheses or set the duration and scope of the experiment. What are we doing? We are expanding population at two to three times the national growth rate in our most water scarce states in the southwest, 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 of them in surface and groundwater, through sewage treatment plants and individual septic systems that were not designed to treat them. These and other examples of our national scale experiment are likely to continue well into the 21st Century. This experiment and related challenges and conflicts will continue and likely intensify as nonclimatic and climatic factors, such as predicted rising temperature and changes in the distribution of precipitation in time and space, continue to develop.

In contrast to many popular media accounts regarding these conflicts, according to Barnaby (2009), nations have never gone to war over water resources. She writes, “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 derive from a number of factors, both new and old. Some of the emerging factors are described below, using examples mainly from the U.S. These are fundamental challenges that are likely to complicate water resources management for much of the 21st Century in the U.S. and abroad.

POPULATION AND LAND USE CHANGE

Population in the U.S. is expanding at two to three times the national growth rate in the Nation’s most water scarce region, the southwestern U.S., where water stress is already great. During the period 1990-2000, Arizona population grew by 40% and population in Nevada by 66%. Growth rates in these two states declined somewhat during the period 2000-2010 to 25 to 35%, but remain high, considering that the national growth rate was 9.7%.

Many high growth states are vulnerable to changes in water availability and quality. Modeling studies predict decreased streamflow in western mid-latitude North America by the middle of this century and attribute this change to increased temperature and evapotranspiration (Karl *et al.*, 2009; Overpeck and Udall, 2010). Colorado River 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 2041-2060, compared to runoff measured during the period 1900-1970

During the period 2000-2005, land use in irrigated agriculture in the U.S. decreased in the west and increased in the east, particularly in the southeastern states, heightening competition for ground and surface water. Total irrigated area decreased by 4% in the west and increased in the east by 5% from 2000 to 2005. Among the eastern states, Arkansas, Mississippi, Missouri, and Florida had the largest withdrawals for irrigation.

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 to assure equity in resource distribution, thereby diminishing conflict

ANTHROPOGENIC SUBSTANCES AND WATER SUPPLY

U.S. consumption of pharmaceutical and personal care products (PPCPs) is at historic high levels, with PPCPs entering surface and groundwater, through sewage treatment plants, individual septic systems, runoff from animal feedlots, and landfill leachate. According to the World Health Organization, the market share of the U.S. alone for global pharmaceutical sales rose from 18% of the world total in 1976 to more than 52% in 2000.

In the first national scale examination of emerging contaminants in streams of the U.S., the U.S. Geological Survey (USGS) collected water samples 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.

These substances are known to have marked effects on aquatic species, particularly on fish reproduction functions. Scientists do not yet 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. 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 below.

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.

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 U.S. (Overpeck and Udall, 2010). USGS studies show that 20th Century warming has already affected salmonid habitat, with unfavorable changes to thermal and hydrologic properties of aquatic systems supporting coldwater fisheries. In work on native trout and grayling in 11 western states, climate model output indicates that these trends will continue and even accelerate until at least the middle of the 21st Century. Drought is the most pervasive threat, with 40% or more of the historic range for seven taxa at a high risk; additionally, increasing summer temperatures and wildfires present higher risks.

The need is great to better understand and manage the whole hydrograph and the influence of hydrologic variability on aquatic ecosystems. 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 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 U.S. 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 multi-year drought exacerbated the conflict, and although the drought was partially mitigated by above average rainfall in late 2009, the regional conflict and drought continue as of this writing (2012).

EFFECTS OF CHANGES IN STREAMFLOW TIMING AND PRECIPITATION TYPE

A critical role for Federal agencies in climate change science is to measure and describe hydrologic 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 hydrologic and meteorologic instrumental records, historical documents, ice cores, tree rings, and lake sediment cores. Precipitation and streamflow patterns have been changing during the past several decades and are predicted to continue to change, with western mid-latitude North America generally drier (Overpeck and Udall, 2010). 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.

Hydrologists have documented trends of more rain and less snow in mountains of the western U.S. This has major implications for water supply and storage, and groundwater recharge. Hydrologists have documented earlier snowmelt peak spring runoff in northeastern and northwestern states, and western montane regions. Peak snowmelt runoff is now about two 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.

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. Recent studies estimate 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 hydrologic trends that vary regionally and temporally. While decreases in streamflow are anticipated in western states, wetter conditions recently have occurred in the mid-continent. In eastern North Dakota, for example, water levels in lakes recently have been at their highest level in 160 years, consistent with a pattern of episodic wetter periods over the past 2,000 years. Increases in streamflow were reported elsewhere in the Great Plains as well, where on average, a 12% increase in annual precipitation led to a 64% increase in streamflow in 10 watersheds in Nebraska, Kansas, and Oklahoma.

SEA-LEVEL RISE AND WATER SUPPLY

Sea-level rise presents challenges for fresh water 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), saltwater movement also results from changes in precipitation, runoff, and recharge that may occur within coastal watersheds. 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.

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. A recent USGS study estimated that global groundwater depletion during 1900–2008 totals ~4,500 km^3, equivalent to a sea-level rise of 12.6 mm (>6% of the total).

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.

The Las Vegas, Nevada, area has seen water consumption decrease by nearly 80 billion liters between 2002 and 2008, despite a population increase of 400,000 during that period. 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 cash incentives for lawn removal, and subjecting golf courses to mandatory annual water budget limits. Significant challenges remain to be solved in this water-scarce region, as urban water needs compete with those of rural domestic water supply, irrigated agriculture, and environmental requirements for sustaining federally listed and water dependent endemic species. State tax incentives are offered for residential properties in Arizona for gray water and rainwater harvesting systems. Additionally, 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, however, 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 U.S. since 1985 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 satellite data; and lastly,
- increased competition for surface water, particularly in western states where most surface water is fully appropriated at present.

Because of these stressors on irrigation, we are likely to see continued improvement in irrigation practices. The USGS recently analyzed more than 30 years of salinity data in streams and groundwater in the southwest U.S. 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.

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. 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, the effects on human health have not yet been well quantified. The U.S. Environmental Protection Agency's Unregulated Contaminant Monitoring Rule (UCMR) requires that public water suppliers monitor selected unregulated contaminants in finished drinking water supplies. 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 U.S.

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, recent studies estimate 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 warms as predicted and if regional water consumption is not reduced. Barnett and Pierce (2009) state 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 U.S. and abroad, as they face the simultaneous reduction in both the quantity and the quality of available water. The USGS is currently developing plans to assess brackish groundwater as a potential water supply source. 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.

Sea-level rise during the 20th Century was 3 to 4 mm per year in the mid-Atlantic region of the U.S. 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.

Lastly, 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 geologic). 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.

CONCLUSIONS

Water resources quantity and quality challenges that we face 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 upon 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. However, as noted in the introduction, according to Barnaby (2009) nations have never gone to war over water resources.

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 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 hydrologic 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.

Scientists have 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, 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 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. 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, complicated this approach.

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; 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 bringing up to date the hydrologic statistics that are central to our planning, design and operations of systems.

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