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Water, People, and the Future: Water Availability for Agriculture in the United States

Abstract

With a projected 25% and 50% increase in U.S. and world population, respectively, by the year 2050, substantial increases in freshwater use for food, fiber, and fuel production, as well as municipal and residential consumption, are inevitable. This increased water use will not come without consequences.

Already, the United States has experienced the mining of groundwater, resulting in declining water tables, increased costs of water withdrawal, and the deterioration of water quality. Long-term drought conditions have greatly decreased surface water flows. Climate change predictions include higher temperatures, decreases in snowpack, shifts in precipitation patterns, increases in evapotranspiration, and more frequent droughts. Not surprisingly, conflicts over water use are continually emerging.

As one of the largest users of water in the United States, agriculture will be impacted significantly by changes in water availability and cost. Approximately 40% of the water withdrawn from U.S. surface and groundwater sources is used for agricultural irrigation. Although the proportion of available freshwater used in agriculture varies widely among geographical areas, it is a major proportion of total water use in every area.

Increasing responsibilities are being placed on agricultural water users at a time when available water resources are decreasing. Additionally, increasing industrial and residential water use will continue to limit the water available to agriculture. Since agriculture faces a future with less water available, substantial efforts will be

In central Arizona, the Santa Rosa Canal provides Colorado River water for cotton, alfalfa, wheat, and other crops. (Photo courtesy of USDA Agricultural Research Service Image Gallery.)

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required to make irrigated agriculture more productive and water-use efficient.

It is important to the economic vitality of the United States—including agriculture—that policymakers, water managers, and water users work collaboratively to achieve sustainable water resource management. Multiple issues require attention—water quality, environmental water needs, municipal demands for water, water resource availability, agricultural water use—and no issue can be addressed individually. This paper discusses the diverse demands for water resources—past, current, and future—using the impacts, regulations, challenges, and policies of specific U.S. states as examples. The authors indicate that the reliability of water quantity and quality deserves the attention of all levels of government and that private and public sector leadership will be critical.

Introduction

As global population grows, the demand for food and fiber also grows, thereby increasing the water demand for household, community, industrial, and energy purposes. Rising standards of living throughout the world also impact water requirements. Despite current uncertainty about the United States' economic future, most reports suggest that growth will resume and competition for freshwater will continue. An abundant, reliable supply of water to meet these demands cannot be taken for granted. Overall, public water supplies account for approximately 10% of all freshwater withdrawals in the United States, whereas irrigation accounts for nearly 40% (USGS 2004). The strong dominance of agriculture compared with municipal consumption of freshwater also is consistent with worldwide statistics.

As one of the largest users of water in the United States, agriculture will be impacted significantly by changes in water availability and cost. The water withdrawn from U.S. surface and groundwater sources for agriculture is used to irrigate more than 63 million acres of cropland. The increase in agricultural water use in some areas of the country coincides with fixed or diminishing water supplies.

Several trends challenge water managers and users. Population continues to grow rapidly; by 2050, the population is expected to increase by 25% in the United States and by 50% globally. Some areas experience a scarcity of water compared with demand. In these and other locations, relic groundwater is being mined, resulting in declining water tables and associated problems that increase the costs of water withdrawal and result in the deterioration of water quality.

In some areas—most notably the Western states—long-term drought conditions have greatly decreased surface water flows. Climate change predictions include higher temperatures, decreases in snowpack, shifts in precipitation patterns, increases in evapotranspiration, and more frequent droughts. How water managers and users respond to these challenges will determine, in part, the long-term availability of water for municipal, agricultural, and other uses, including those of riparian systems.

This paper provides insights into how these challenges to water availability are being addressed in four specific areas of the United States: California, Arizona, Florida, and the High Plains region, with particular focus on the implications for agriculture. These experiences will be helpful in developing solutions to similar water issues faced by many other regions of the country and world.

Case studies of water use and availability are necessary because laws and regulations differ by state and often by region within a state. For example, Arizona and California are two of seven states sharing the Colorado River with Mexico; management of the Colorado River is unlike that of any other river in the nation. States in the High Plains region share a large but diminishing aquifer. Florida has abundant water supplies, but environmental needs also are great, and available supplies are not necessarily of the quality and in the location required by the growing demand.

The legal framework for water management also differs among these areas. The Western states tend to rely on the "doctrine of prior appropriation" for the allocation of rights to use water, whereas the Eastern states traditionally allocate water through "riparian rights." California uses both systems. Water is allocated using prior appropriation

based on the historic timing of withdrawals for beneficial use.

In a pure riparian system, the rights to use water are limited to owners of land that borders or overlies a body of water and those rights are limited to what is reasonable, considering the needs of other landowners. Both systems—prior appropriation and riparian rights—have been modified significantly in practice and among different jurisdictions. In some ways, the systems are increasing in the similarity of their application, partly the result of increasing regulatory and administrative complexity in the states' implementation of water rights.

In some prior appropriation jurisdictions where private water rights are most secure, limitations on water use have increased based on the impact to other users, ecosystems, and public interest considerations. Whereas many riparian jurisdictions now provide greater protection for existing users, increasing nonagricultural water use demand will challenge communities in reallocating water resources to meet demand. Regardless of the underlying framework—and perhaps of greatest consequence to agriculture—is the increasingly recognized link among water use, ecology, and water quality. This link has a strong regulatory foundation in the Endangered Species Act (ESA), state and federal water quality regulations, the public trust doctrine, and other public interest considerations (Blumm 1989).

Groundwater use is regulated differently from surface water, where groundwater is regulated by individual states. Groundwater use regulations also differ substantially across states and sometimes within a state, as the discussion of Arizona demonstrates.

Water use rights also will reflect the ease with which water transactions can occur. Over time, water rights may change through temporary or permanent transfers as nonagricultural water demand increases. Water management reflects a complex, ever-changing legal and institutional framework. As the case studies illustrate, it is important to the economic vitality of the United States—including agriculture—that policymakers, water managers, and water users work collaboratively to achieve sustainable water resource management.

Water Resource Sustainability in California

Water Supply: Background

In an average water year, California receives approximately 200 million acre-feet (MAF) of water, 95% of which comes from precipitation. The remainder is imported from Oregon, Mexico, and—mostly—the Colorado River. More than 80 MAF are allocated to urban (including industrial and commercial), agricultural, and environmental water uses (Table 1). California's population (approximately 35 million) uses water in many different forms:

- urban water (8–9 MAF), which is distributed through public water purveyors and meets industrial, commercial, household (hygienic, cooking, laundry), and homeowner irrigation needs; (bottled water use—at approximately thousand-fold higher cost than tap water—is estimated to be on the order of 3,000 to 5,000 AF);
- agricultural water (34 MAF), which is used to meet crop consumptive needs and, ultimately, is consumed in the form of food (fruits and vegetables, grains, meat, dairy products) and clothing; and
- environmental water (40 MAF), which includes instream flows, wild and scenic flows, required Delta outflow, and managed wetlands water use.

Approximately one-third of the applied agricultural water percolates back to groundwater or returns to streams as tailwater. Environmental uses account for another 40 MAF annually (CDWR 2005). California's population is predicted to nearly double—to 59 million—by 2050. The additional water demand will be met largely by conservation, reuse, and retirement of agricultural water uses (land conversion).

Table 1. California water supply and water use* (CDWR 2005)

	1998 (171% of normal)[a]		2000 (97% of normal)[a]		2001 (72% of normal)[a]	
Total supply (precipitation and imports)	336.9		194.7		145.5	
Total uses, outflows, and evaporation	331.5		200.4		159.9	
Net storage changes in state	5.5		–5.7		–14.3	
Distribution of dedicated supply (includes reuse) to various applied water uses:						
Urban uses	7.8	(8%)	8.9	(11%)	8.6	(13%)
Agricultural uses	27.3	(29%)	34.2	(41%)	33.7	(52%)
Environmental water[b]	59.4	(63%)	39.4	(48%)	22.5	(35%)
Total dedicated supply	94.5		82.5		64.8	

*Measured in million acre-feet (MAF)

[a] Percent of normal precipitation. Water year 1998 represents a wet year; 2000, average water year; 2001, drier water year.

[b] Environmental water includes instream flows, wild and scenic flows, required Delta outflow, and managed wetlands water use. Some environmental water is reused by agricultural and urban water users.

California's water landscape is driven by a temporal and spatial disconnect between its major source of water and the water users: Although most water is available during the winter in the mountainous northern and eastern part of the state (Figure 1), most water usage occurs during the summer in the southern low-lying half of the state (the Bay-Delta region and southward). Throughout the last century, California has undertaken massive water projects to manage this mismatch in time and space between water supply and demand. For example, winter precipitation and spring snowmelt runoff are stored in reservoirs that line the foothills of the California mountain ranges; these reservoirs store water for redistribution during the summer months. A system of large canals tied in with the major streams (Central Valley Project, State Water Project, and others) delivers water from the northern part of the state to the southern region (Figure 2). Southern California also receives much of its water supply (approximately 4.4 MAF per year) from the Colorado River, primarily for irrigation. Colorado River water constitutes slightly less than one-quarter of the urban water supplies in Southern California.

Historically, annual groundwater use has fluctuated substantially in response to year-to-year variations in precipitation, snowfall distribution, and ensuing surface water supplies behind California's reservoir dams (Figure 2). Groundwater use varies from approximately 10 MAF in a wet year to nearly 20 MAF in a dry year. This variation in groundwater use represents from one-third to more than one-half of California's urban and agricultural water use.

Although California's surface water storage system is designed to store water from winter months (wet) for delivery in the summer months (dry), it is not designed to retain water for much more than approximately 2 years. Long drought periods (3–8 years), which California has been experiencing with some frequency, put a major strain on groundwater supplies. Conservation, groundwater banking (storage and recovery), and conjunctive use of groundwater and surface water resources have been used for risk management during these long-term droughts. Construction

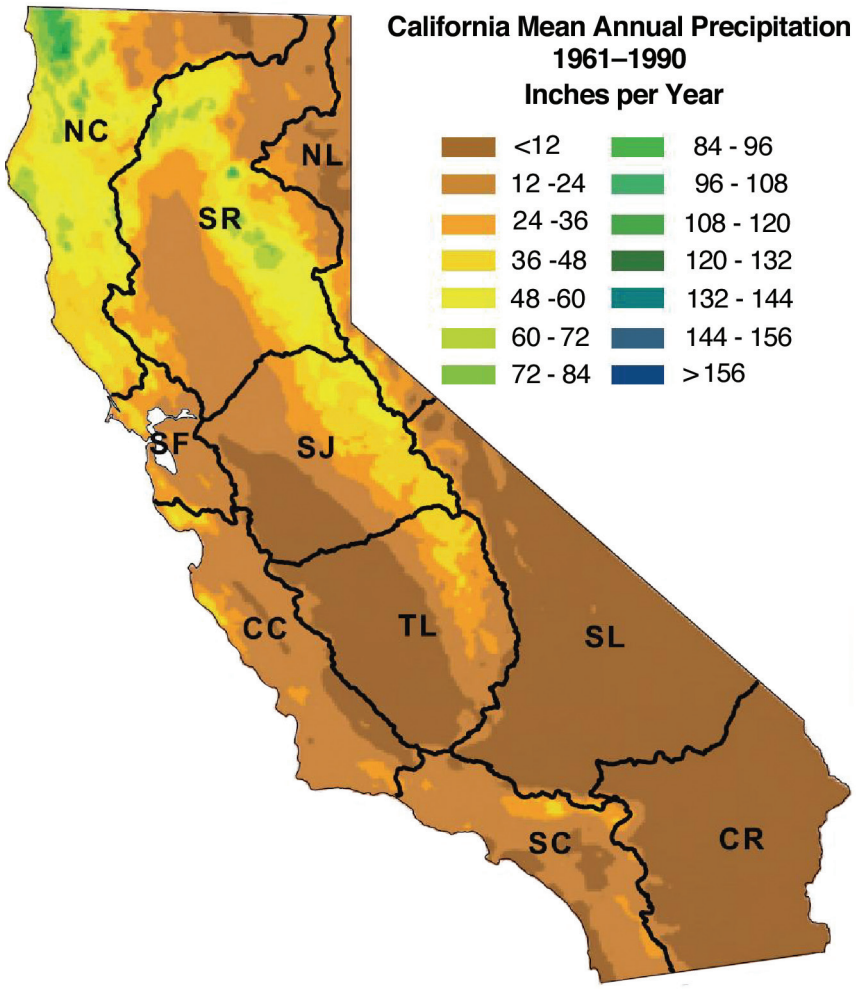

Figure 1. Average precipitation in California, 1961–1990 (CDWR 2005). Boundaries indicate the major watersheds/watershed regions in California. NC: North Coast, NL: North Lahontan, SR: Sacramento River, SJ: San Joaquin River, SF: San Francisco Bay, CC: Central Coast, TL: Tulare Lake basin, SL: South Lahontan, SC: South Coast, CR: Colorado River.

of massive new reservoirs has not been a politically viable option. Only a limited number of new dams currently are being considered for feasibility. Hence, California's water supplies continue to be vulnerable to extended drought and to the physical integrity and ecological health of the state's water storage and distribution systems.

Water Rights

To manage water within these large-scale constraints, California's water rights system makes a strong distinction between surface water rights and groundwater rights (Harter 2008). Most surface water available in an average water year has been assigned a water right and is managed accordingly. Water rights follow a mixed system of riparian and prior appropriation rules and are governed by California's constitutional mandate that water be put to maximum beneficial use. The State Water Resources Control Board is the state's water rights authority.

In contrast, most groundwater is pumped without any direct control by a state agency, and groundwater rights are governed in compliance with the "correlative rights doctrine." The right to groundwater is defined as a "usufructuary" right (i.e., the right to use or enjoy as opposed to outright ownership) that is an appurtenance of the overlying land (not extinguished by nonuse). The right to use groundwater is shared by all overlying owners of a groundwater basin. No water right permits are needed to pump groundwater, except in the few groundwater basins (mostly in southern California) that are fully adjudicated and monitored by a water master.

Figure 2. California topography and water projects to store and redistribute water (CDWR 2005).

Groundwater use outside the basin of origin is governed through prior appropriation and other contractual rules.

Groundwater use is subject to local government restrictions and often to intense public scrutiny unless historically established. Storage and recovery of groundwater is handled separately, with groundwater management handled through the leadership of local agencies or groups of agencies. Since the mid-1990s, local agencies have prepared groundwater management plans; although the plans vary widely in scope, they are prerequisites for local agencies to receive any groundwater-related state funding. More recently, state funding for water projects requires implementation of Integrated Water Resources Management Plans (IWRMPs). These plans allow local agency management not only of water resources but also of water quality across legal boundaries, across surface water and groundwater rights, and across federal and state laws that focus on portions of the water system but otherwise fail to provide for an integrated process.

Water Supply Decreases for Environmental and Water Quality Protection

Surface water rights, together with most major dams and canal distribution systems, were fully established by the 1970s, but recent legal developments to protect endangered species and water quality have challenged existing surface water rights (Harter 2008). Since 1983, court decisions have given recognition to the Public Trust Doctrine, from which the state holds sovereign ownership of all tidelands and the beds of all navigable lakes and streams, holding the trust to these lands in perpetuity for the beneficial use of the people. California courts have affirmed that the state may continuously exercise control of its water rights if those rights affect ecological health and scenic beauty. This state control has impacted, for example, the amount of water that the City of Los Angeles can divert from tributaries to Mono Lake, a terminal lake east of Yosemite National Park with a unique ecosystem. These controls also have impacted the management of dam water releases for maintaining instream flows sufficient to meet stream fishery demands.

Through the federal ESA, federal, state, or local government actions are prohibited from impacting the health of an endangered fish or other aquatic species. The protection of endangered fish species in the unique and highly complex Bay-Delta region is of particular concern to California (Figure 2). Water from Northern and Central California reservoirs is delivered by the Sacramento River and San Joaquin River to the Bay-Delta, and from the southern part of the Delta, water is pumped into large canals delivering water to destinations in Central and Southern California. The Bay-Delta region, therefore, has become the state's central "water hub" and is a key nexus between Northern California's water supplies and Central and Southern California's water users (Figure 2).

Recent court decisions to protect endangered fish species in the Bay-Delta region decreased the amount of water that may be channeled through the Bay-Delta by an estimated 20 to 30%. These mandated delivery decreases at the state's central water hub are creating a permanent "drought" in the central and southern half of the state. For decades, an alternative solution to channeling water directly through the Bay-Delta region has been sought. One alternative, a "peripheral canal," would route water from the Sacramento and San Joaquin Rivers just upstream of their mouths via a canal around (and circumventing) the Bay-Delta region directly into the State Water Project and Central Valley Project canals. The idea was rejected by Northern California voters in 1982.

Heightened awareness of the Bay-Delta's ecological health, the aging infrastructure of the levee in the Bay-Delta, ripened water markets, and court-mandated decreases in water deliveries have revived discussion about the construction of a peripheral canal or similar alternative. As part of the Bay-Delta water transfer infrastructure discussion, additional surface water storage is being evaluated to alleviate the resulting decreases in urban and agricultural water supplies, resulting, in part, from ESA enforcement.

Two other major water supplies in California have been affected by enforcement of the ESA. In far Northern California and Oregon, protection of salmon fisheries is changing the management of dams in the Klamath River basin, with the possibility that some of the first major dam removal projects will occur in the near future. In Central California, the salmon fishery of the San Joaquin River is scheduled for restoration. This will require additional in-stream releases of nearly 1 MAF per year from Millerton Reservoir (Figure 2).

Water will be taken from the federal Central Valley Project, which otherwise provides irrigation water for the southern San Joaquin Valley and eastern Tulare Lake region (Figure 3). Agricultural stakeholders are hoping to meet their future water needs through alternative means, including conjunctive use and groundwater banking, water exchanges (although impacted by the limited operability of the Bay-Delta hub), and possibly by additional surface water storage within the San Joaquin River and Tulare Lake Basin watershed.

The Clean Water Act (CWA) is impacting urban and agricultural water supplies in California. Although its primary function has been the installation of wastewater treatment plants to improve water quality from point discharges to rivers and lakes, the CWA has focused on establishing and managing Total Maximum Daily Loads (TMDL), leading to additional treatment requirements for point sources and management of nonpoint sources as well as reevaluation of the management of surface water flows as a means to alleviate water quality impacts. In a few instances, where natural summer stream flows are influenced and supported exclusively by groundwater discharge to streams—"baseflow" (which differs from stream flows created by reservoir releases)—groundwater pumping has been identified as having a direct impact on surface water quality. It remains to be seen to what degree TMDL enforcement will lead to direct impacts on groundwater management through baseflow requirements.

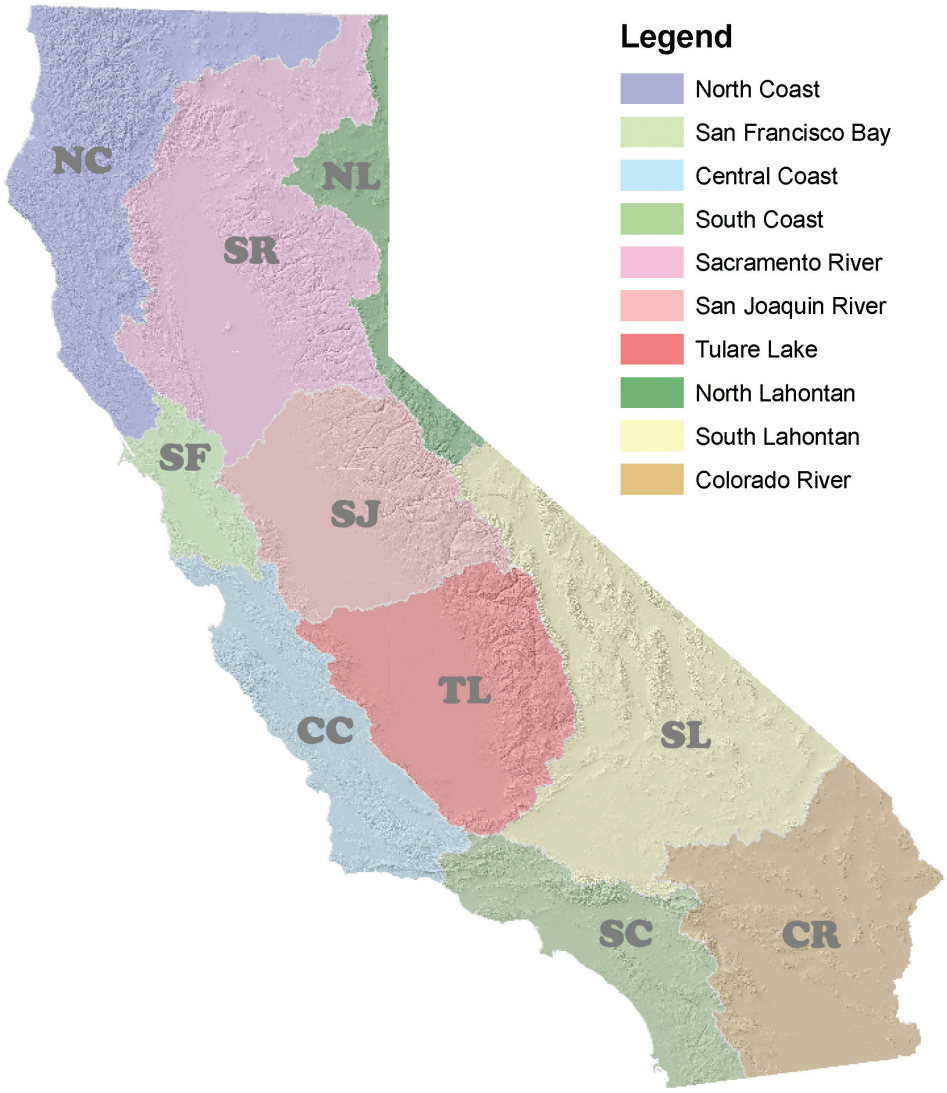

Figure 3. Hydrologic regions of California (CDWR 2009).

These pressures are putting a significant strain on an already unbalanced system. Before the recent changes in surface water allocations resulting from ESA and CWA enforcement, California experienced a long-term shortage of 1–2 MAF per year between total renewable water supplies and total water use. The shortage is taken out of groundwater storage ("overdraft") permanently. The major areas of overdraft are in the Southern San Joaquin Valley, in eastern San Joaquin County, and in a handful of coastal basins. To what degree the recent changes in surface water allocation will affect the groundwater overdraft currently is not known.

Agriculture and Water Quality Regulations

California agriculture is experiencing the beginning of major changes that eventually will lead to increased regulatory oversight to address issues dealing with surface water quality and groundwater quality. California's Porter-Cologne Act, unlike the federal CWA, regulates not only discharges to—and water quality in—surface water, but also discharges (through percolation or direct injection) to groundwater and basin-wide groundwater quality. But discharge of tailwater or precipitation

runoff (to streams) and percolation of excess irrigation water to groundwater have been exempt from regulatory oversight.

Recent changes in California law effectively have removed these exemptions; landowners now need to obtain permits for all discharges. The permit may take the form of a "conditional waiver" (requiring the landowner to submit information regularly about water quality and management practices) or an outright "discharge permit" subject to public review and frequent regulatory inspection. Currently, most landowners are participating in regional coalition groups to meet the water quality monitoring requirements of the irrigated lands waiver. Sediments, pesticides, nutrients, and salt are the major (surface) water quality concerns. The current focus of the irrigated lands discharge program is on discharges to surface water. Eventually, the program also will monitor discharges to groundwater on agricultural operations. Inclusion of groundwater monitoring will be, by far, the largest expansion of a groundwater quality monitoring program in California's history, ultimately affecting most of California's 9 million acres of irrigated lands.

Confined animal facilities operations (CAFOs)—specifically dairies in the Central Valley, which comprise most of the state's CAFO industry—currently must comply with rigorous regulatory programs from both air and water quality regulatory agencies. An outright requirement for groundwater monitoring was imposed by a new (and first) 2007 permit program for Central Valley dairies. The Central Valley houses almost 1.5 million milking cows, not including the necessary support cattle (calves, heifers, dry cows), and produces more than 15% of the nation's milk and cheese supply. California is the largest dairy producing state in the country. The dairy waste discharge requirements program is a massive shift in the state's regulatory approach relative to agriculture and the first nationwide program explicitly created to protect groundwater quality (surface water discharges have been prohibited since the 1970s). Although it is the first such agricultural groundwater monitoring program of this scale in the country, it is likely that the dairy groundwater monitoring program, still being developed, eventually will become a model groundwater monitoring program for all irrigated lands in the Central Valley and elsewhere in California.

These developments represent a major shift in the role that agricultural business takes in water quality management and monitoring, at significant cost to landowners. It currently is not clear what remedial actions will be required or what the cost to the agricultural sector will be in areas where groundwater quality is impacted.

Other regions, such as the Salinas Valley, are managing the looming threat of widespread nitrate contamination from fertilizer applications through local and regional water agencies; volunteer groundwater monitoring networks consisting primarily of production wells (as opposed to dedicated monitoring wells); and extensive outreach, education, and incentive programs to growers, irrigators, and fertilizer consultants. In the Salinas Valley, widespread adoption of new irrigation technologies decreases the amount of irrigation water percolation to groundwater, allowing a more targeted application of nutrients to match weekly varying crop nutrient uptake requirements. Regional groundwater quality trends in the Salinas Valley show a halt in the increase of groundwater nitrate contamination, but there are few case studies determining actual groundwater quality impacts from specific irrigation and fertilization practices.

Groundwater Resources: Planning for the Future

Through legislation, the state has encouraged local agencies to work cooperatively toward regional groundwater management and groundwater quality protection. Groundwater management plans have been developed by local agencies since the early 1990s, although these plans may vary widely in the extent of review, understanding, and management of groundwater resources. More recently, groundwater management plans have been superseded with requirements that IWRMPs be developed as a prerequisite for obtaining state funding for water-related projects. The IWRMPs explicitly recognize the integrated aspects of managing surface water and groundwater resources for both water supply requirements (urban, agricultural, and environmental) and for water quality protection. The IWRMPs are developed cooperatively by local and regional agencies and by stakeholders with an interest in the water resources of a region.

Other recent driving factors for regional water management include new laws requiring developers of subdivisions with 500 or more units to provide a water supply assessment before obtaining a land development permit from the local land use agencies. The assessment must determine if there is sufficient supply during a normal year as well as during multidrought years and must consider all existing uses. For surface water, water rights must be available or be secured; for groundwater, a complete basin analysis of groundwater supplies must be implemented, even if the subdivision occupies only a fraction of the basin's land. These developments put significant pressure on developing IWRMPs and ultimately may lead to additional groundwater adjudications as agricultural land is converted to an urban landscape.

Finally, recent anticipated changes in the regulatory requirements addressing the Safe Drinking Water Act (SDWA)—specifically the addition of new constituents to the list of contaminants regulated by the SDWA—and the lowering of the maximum contaminant levels for some naturally occurring groundwater constituents (especially arsenic and chromium) is driving some California municipalities to evaluate options for switching from groundwater to surface water supplies as their source of drinking water.

Upcoming Challenges

California agriculture faces challenges from water issues in the coming years. Enforcement of laws protecting surface water quality, aquatic ecology (endangered species), and other beneficial environmental and recreational uses of surface water supersedes significant portions of existing water rights. This problem is caused by the inability of the existing infrastructure to store and move water across the state without impacting water quality and aquatic ecosystem health. The potential consequences of climate change encompass a wide range of scenarios and likely will tax the existing water resources infrastructure,

particularly if scenarios of decreased snow-pack, shorter winter seasons, and more erratic weather conditions prevail. Meeting agricultural, urban, and environmental water demands will require

- a significant expansion of groundwater banking, possibly combined with a judicious and limited expansion of surface water storage;
- improved conveyance through or around the Bay-Delta region, the most critically impacted region within the state's water redistribution and delivery system;
- a decrease in the consumptive use of water—particularly in the urban sector, which will continue to expand into California's agricultural lands;
- water conservation and reuse;
- desalination; and
- continued improvement of irrigation efficiency and agricultural productivity.

Agriculture is facing unprecedented pressure for environmental monitoring and self reporting and for implementing stricter management practices that provide significant, proven safety to water resources. There is much room for research, development, and capacity building. Creative and economically efficient solutions need to be developed and implemented to meet these environmental challenges and to define regulatory programs that are simultaneously efficient to implement and effective at ensuring environmentally sustainable agricultural management.

Both environmentally related decreases in surface water deliveries and active protection of surface water and groundwater will force agriculture to continue to improve irrigation efficiency, practice more efficient nutrient management (fewer nutrient losses to the environment), and institute "smarter" pest management programs. Irrigation efficiency alone does not decrease net (consumptive) water use by agriculture. It is important to recognize that excess irrigation water simply returns to groundwater or to surface water and frequently is reused. In some areas, inefficient irrigation already is an important element of incidental or managed groundwater banking and conjunctive use.

The extent to which deficit irrigation (intentional decrease of crop consumptive use) or alternative crops with lower consumptive use can provide real water savings in the agricultural sector remains to be evaluated. At the regional and statewide levels, permanent, long-term decreases in water supply to agriculture translate directly into decreased agricultural production, even if irrigation efficiency is increased. Hence, the political leadership and the people of California ultimately need to determine the degree to which the state wants to support food and fiber production in light of the trade-offs associated with urban and environmental water needs.

Water Resource Sustainability in Arizona

Arizona is a rapidly growing, semi-arid state, and the water supplies that support its agricultural activities and nonagricultural economies vary across the state. Arizona is home to two large U.S. Bureau of Reclamation Projects—the Salt River Project (SRP) and the Central Arizona Project (CAP)—and municipal and agricultural water demands have been able to coexist. But continued population growth is expected to place even greater pressures on Arizona's finite water supplies, and identifying water supplies to accommodate additional people is the subject of active discussion and debate. The management of Arizona's water supplies is a key concern of all water-using sectors in the state.

Annual water use in Arizona is estimated to be close to 8 MAF, or 2.3 trillion gallons, of freshwater (McClurg 2007). Agriculture accounts for the majority of freshwater withdrawals (74%), followed by municipal (20%) and industrial (5%) uses (ADWR 2007). More than 900,000 acres of land in Arizona are irrigated and harvested each year (USDA–NASS 2004).

Half of Arizona's water withdrawals currently occur within Active Management Areas (AMAs) (Figure 4), where groundwater use is regulated by the Arizona Department of Water Resources (ADWR) (Arizona Town Hall 2004). The AMAs include the two largest cities in the state (Phoenix and Tucson) and more than 80% of the state's 6.5 million people. Although less populated, many of the state's rapidly growing areas are outside the AMAs.

Freshwater Sources

Surface water supplies satisfy a portion of Arizona's consumptive water needs (Colby and Jacobs 2007). Average annual supply of surface water from in-state rivers is about 1.4 MAF, and 2.8 MAF is allotted from the Colorado River for use in Arizona (ADWR 2007). About 479,000 AF of effluent is produced annually, an amount that is increasing as municipal uses grow, but is limited in availability in smaller cities. About 2% of demand in 2003 was served by treated effluent (Figure 5).

These water sources vary considerably depending on geography. Colorado River water is used by irrigation districts, Indian Tribes, and cities located on the river, which traces the western boundary of the state (ADWR 2007). More than half of Arizona's Colorado River allotment is delivered via the CAP to three counties in central and southern Arizona. In addition to CAP supplies, provided by the Central Arizona Water Conservation District (CAWCD), the greater Phoenix region also relies on imported surface water distributed through the SRP from the Salt and Verde Rivers. Surface water, including CAP water, provided 52% of water used in Arizona in 2003 (ADWR 2007).

Salinity is a major issue for Arizona surface water quality and only has been addressed by nonregulatory programs that encourage best management practices (Colby and Jacobs 2007). The Colorado River is the largest saline water supply for Arizona, the result of concentrating effects of human activity and natural sources of salt in its headwaters (Gelt 1992). Recycling of water to extend supplies also can result in increased salinity levels. Salinity in irrigation water affects crop production and yields; in public supplies or industrial processes, salinity often makes water unfit for direct use without extensive treatment.

Although the groundwater supply in Arizona represents the largest reserve of freshwater available in the state, most groundwater (75%) is stored in the southern and western portions of the state (ADWR 2007; Freethey and

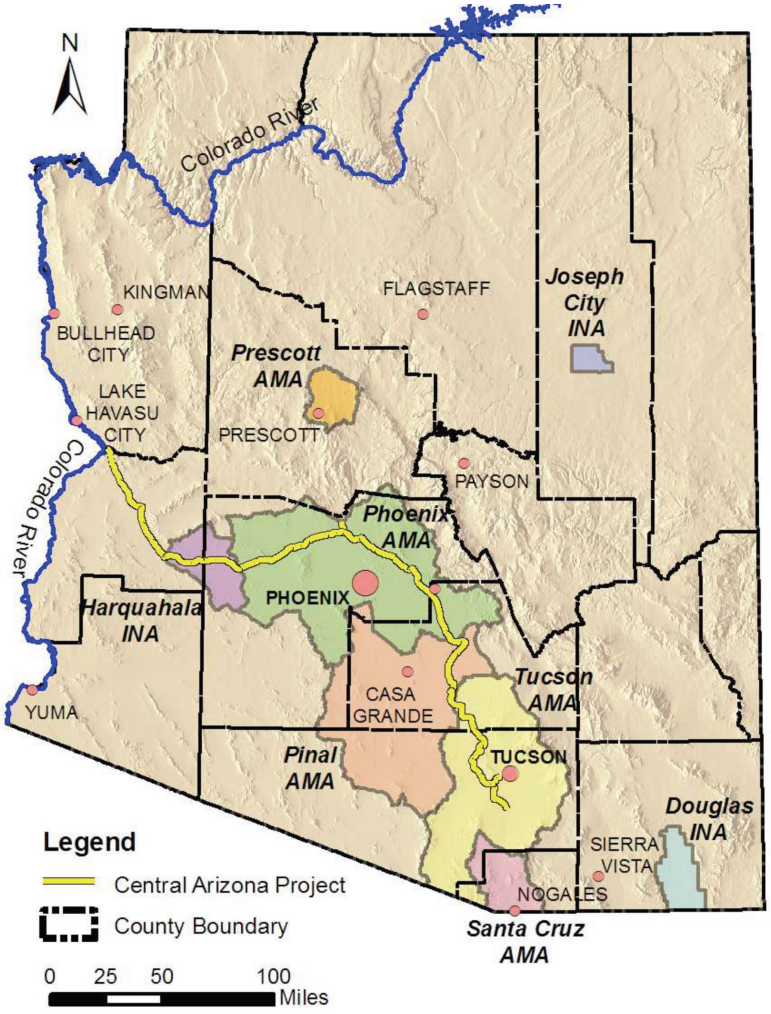

Figure 4. Arizona Active Management Areas (modified from ADWR 2007).

Anderson 1986). Groundwater provided 46% of the 7.8 MAF of water used in the state in 2003 (ADWR 2007), and regional groundwater quality varies. Groundwater in Arizona is generally of higher quality than surface water, requires less treatment before delivery, and is more reliable in the face of climate variability (Colby and Jacobs 2007). But deeper groundwater often is unsuitable for potable use without additional treatment (ADWR 1999, 2003;

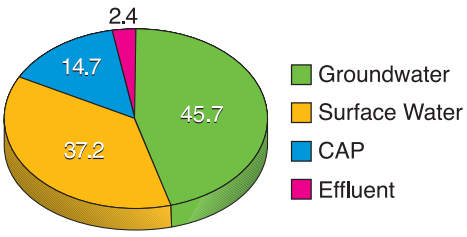

Figure 5. Arizona water demand (ADWR 2007).

Marsh 2000; Owen-Joyce and Bell 1983). Also, in certain urbanized areas and in areas with historical agricultural and mining activities, shallow groundwater is high in salinity or displays signs of contamination (Brown and Favor 1996).

Groundwater pumping beyond the amount naturally renewed through recharge (i.e., groundwater mining) has had some detrimental effects in Arizona. Pumping of groundwater from lower levels of the aquifer requires significant energy to lift the water and to treat lower-quality water. Another consequence of mining groundwater is subsidence, which in some places has created cracks in the earth, or fissures, that stretch for miles. Finally, groundwater pumping has degraded 90% of Arizona's once-perennial streams and riparian habitats (Glennon 2002). Although there are spacing rules for wells within the AMAs, regulations do not limit the placement of wells elsewhere in the state.

Uses of Water

Statewide, agricultural freshwater withdrawals totaling 5.4 MAF (more than 70% of all withdrawals in Arizona) come from relatively equal amounts of groundwater (45.7%) and surface water (42.2%). Compared with freshwater demand by other uses, agriculture relies on a somewhat smaller proportion of surface water to meet its demand. Slightly more than 10% of agricultural withdrawals are supplied by CAP water, and the remaining agricultural demand (1.3%) is served by treated effluent. Agricultural water is used to meet crop consumptive needs and ultimately is used in the form of food (fruits and vegetables, grains, meat, dairy products) and clothing.

Groundwater provides more than one-half (54%) and the CAP provides one-third of the 1.8 MAF of water withdrawn for irrigation within the AMAs; the remaining agricultural demand is met by local surface water supplies and use of reclaimed water. CAP water is made available to agriculture by CAWCD at a lower price than is paid by municipalities and from municipalities in exchange for groundwater storage credits through the groundwater savings program, one of Arizona's authorized storage and recovery programs (Colby and Jacobs 2007; Megdal and Shipman 2008).

In rural portions of Arizona and in cities and towns outside the AMAs, there are fewer options for access to alternative water supplies. Outside AMAs, agricultural water demand is more than twice the agricultural demand inside AMAs (ADWR 2007). Agricultural users in rural areas rely on local surface water (58%) and groundwater (42%) to serve their 3.7 MAF in demands. Southwestern Arizona's agriculture is served by the Colorado River, whereas southeastern Arizona's irrigated agriculture is mostly served by groundwater (ADWR 2007).

Municipal demands within AMAs (17% of all demand) use groundwater (35%), CAP (31%), surface water (27%), and treated effluent (7%). With surface water sources nearly fully used or committed, treated wastewater is

becoming an increasingly important component of municipal water supply portfolios and will not be as readily available for other sectors (Megdal 2007).

Municipal freshwater use outside AMAs is much lower than that within AMA boundaries, and the population is served mostly by groundwater (77%) and locally by surface water (23%). Industrial users in rural areas generally rely on groundwater with supplemented supplies from local streams and treated effluent.

Past Trends in Water Use

Municipal water uses and industrial uses increased in almost all counties between 1990 and 2000. During this period, mining water uses dropped and irrigation uses declined moderately, led by decreases in Maricopa and Pinal Counties.

Groundwater was the major source for agricultural use until 1980, when imported Colorado River water became available (Konieczki and Heilman 2004). Irrigated acres in Arizona have been decreasing since 1975, despite a brief peak in the mid-1990s (Konieczki and Heilman 2004; USDA–NASS 2004). The most noticeable recent decrease in irrigated acreage occurred in central Arizona (Frisvold 2004); between 1984 and 1995, 60,000 acres of farmland in the Phoenix AMA (out of 389,000 irrigated acres) went out of production because of conversion to nonirrigated uses (Gelt 1999). Rapid urbanization has led to conversion of many agricultural lands for development and the use of new lands for agriculture. In contrast to the statewide trend, two western counties—Yuma and La Paz—showed long-term increases in harvested acreage, and irrigated acres increased in Cochise, Gila, Mohave, and Pima Counties (USDA–NASS 2004) between 1997 and 2002 (Table 2).

Historically, agricultural trends have led total water use trends. Changes in crop mixes since 1990 have included increased use of water-intensive crops such as alfalfa, vegetables, and melons (Cohen and Henges-Jeck 2001; Colby and Jacobs 2007; USDA–NASS 2004). In Maricopa County, decreases in irrigated water use between 1990 and 2000 led to decreases in overall county water use despite simultaneously increasing municipal demands (Arizona Town Hall 2004).

Table 2. Acres irrigated in Arizona (USDA 2007)

County	Acres irrigated and harvested in 2002
Maricopa	232,451
Pinal	207,635
Yuma	197,038
La Paz	90,757
Cochise	58,063
Graham	32,298
Pima	32,101
Mohave	20,117
Apache	5,272

Water Management

Water management has long been a focus in Arizona, and groundwater and surface water availability have been key determinants of the location of economic activity. The completion of the SRP in 1911 and the CAP in 1993 has enabled central Arizona to thrive. But concerns about overdraft of groundwater aquifers led to the 1980 adoption of the Groundwater Management Act (GMA). The GMA designated overdrafted groundwater basins as AMAs, where groundwater use would be regulated (Figure 4). Each AMA has a statutory groundwater management goal, and regularly revised management plans establish conservation regulations for the municipal, industrial, and agricultural sectors (Megdal, Smith, and Lien 2008). The ADWR was established to implement and enforce the GMA. The Arizona Department of Environmental Quality was established in 1987, and since its inception has had significant state-level water quality oversight and, more recently, has assumed responsibility for enforcing federal water quality regulations in the state. Water quality regulation is essential to human health and safety and is associated with considerable challenges for managers, but the more direct impacts on agriculture in Arizona emanate from water supply regulations.

To address demands on groundwater in municipal areas, the GMA restricted agricultural activity in the AMAs to the maximum acreage historically irrigated during the late 1970s. The GMA also established Irrigation Non-Expansion Areas (INAs). Although agriculture cannot expand beyond the footprint of the late 1970s, groundwater use in INAs is not regulated otherwise. A key feature of the GMA was the requirement that rules be established governing the use of groundwater by the growing municipal sector.

Adopted in 1995, the Assured Water Supply Rules require that new residential development within the AMAs demonstrate an assured water supply for 100 years. In certain AMAs, the rules require significant use of renewable water supplies to achieve management goals (McClurg 2007).

Although the GMA established groundwater regulations for the AMAs, surface water use continues to be governed by the first-in-time, first-in right doctrine, and use of treated wastewater or effluent is subject to yet a different set of regulations. The general absence of groundwater use regulations outside AMAs, coupled with the absence of conjunctive management of surface water and groundwater inside AMAs, makes for a complex system of water laws and practices (Colby and Jacobs 2007).

Drought Implications

Recent drought conditions have impacted the water supply across the West, decreasing reservoir levels on the Colorado River system to 40-year lows. The Salt and Verde Rivers, source waters for the SRP, have experienced highly variable precipitation in recent years, with the large Roosevelt Lake in the SRP system at 28% of capacity in 2005. Decreases in groundwater levels have been documented widely (Arizona Town Hall 2004). Changes to water availability resulting from future droughts or climate change may impact water users in all sectors, but the impact on agricultural users in central Arizona could be most severe. Future impacts may be felt most in the CAP system, as shortage-sharing agreements have given the largest decrease responsibilities to Arizona (USDOI 2007). Decreases in CAP deliveries will be experienced first by non-Indian agricultural users within the CAP service area, who hold the most junior water rights.

Projected Future Trends

Non-Indian agriculture faces growing competition for water from many sources, such as growing household and industrial demands, Native American tribal claims and water settlements, and, potentially, water for riparian habitats and endangered species (Colby and Jacobs 2007). Arizona's population is expected to almost double by 2050 (AZDES 2006), and predictions for future agricultural water use in Arizona are mixed. Urbanization of lands within AMAs will result in less irrigation by non-Indian agricultural entities as agricultural lands and water supplies are increasingly used by urban and industrial areas and AMA regulations limit agriculture to historically farmed lands. In contrast, in areas outside AMA boundaries, agricultural acreage and water use may increase, depending on a host of factors, including federal agricultural programs. Tribal water settlements have increased the water available to Indian nations located in Arizona, resulting in some increase in agricultural activity.

Although the GMA regulates groundwater use by urban development and limits irrigation expansion within AMAs, the lack of an enforceable water availability requirement for urban development or limits to agricultural expansion outside AMAs may result in many rural communities facing water supply issues much like the already-urbanized areas (Colby and Jacobs 2007). In addition, growing populations and new agricultural demands shifted to rural areas from urban areas may result in the overallocation of limited surface water supplies and mining of groundwater. Future increases in fuel and energy costs will contribute to higher groundwater pumping costs. Increased groundwater pumping also can affect surface water flows, and recent legal recognition of subflow rights may increase conflicts between groundwater users and surface water rights-holders (Colby and Jacobs 2007).

If increases in agricultural production continue in the southwestern corner of the state, there could be increased competition for water between agriculture and municipalities along the Colorado River. Kohlhoff and Roberts (2007), however, predict that conversion of agricultural land around Yuma to urban uses will result in newly available Colorado River supplies for municipal use. Given evidence from Maricopa County, the conversion of agricultural lands may bring new lands into agriculture or to a decrease of agricultural acres in urbanized areas (Hetrick and Roberts 2004). Therefore, the question of whether cities can rely on decreases in agricultural water demands to meet their future needs requires further study. The character of responses to production losses may depend on commodity prices and the availability of water supplies further from the urban fringe.

Large-scale market changes and state and federal policy changes affect relative profitability among crops and may shift Arizona agriculture to produce less water-intensive crops. Despite implementation of AMA agricultural conservation requirements, the flexibility of current efficiency requirements has provided little incentive for significant decreases in agricultural water use (Frisvold 2004; Megdal, Smith, and Lien 2008). Crop mix choices can have a significant impact on the amount of agricultural water required to sustain farming. Provision of payments from the federal government to offset market prices and to encourage resting of agricultural lands in Arizona exceeded $1.3 billion in 2003 (Frisvold 2004). Conservation programs—such as the U.S. Department of Agriculture's Conservation Reserve Program—that encourage dryland farming have been ill-suited to farmers in semiarid Arizona, who must rely on irrigation for their agricultural production.

Agricultural water demand can be decreased through irrigation efficiency improvement, water-efficient agronomic practices, and crop adjustment or retirement. Shifting from gravity or surface irrigation systems to drip or sprinkler irrigation could decrease water requirements for some crops by as much as 50% while increasing yield (Murphy 1995; Wilson, Ayer, and Snider 1984). The Colorado River Salinity Control program included incentives for using more efficient irrigation and delivery systems (Colby and Jacobs 2007).

Improved irrigation efficiency may not lead to a decrease in total usage, however, but rather may decrease return flows (Frisvold 2004). Possible modifications to farming techniques—including the use of agronomic practices such as incorporation of organic materials into the soil, use of mulch, and adjustment of tillage practices—contribute to water use efficiency (Chhetri 2006; Zhang and Oweis 1999). Finally, consideration of economic returns per unit of water consumption may inform crop choices, such as encouraging a switch from cotton to vegetables (Morrison, Postel, and Gleick 1996).

Conclusions

Agriculture is critical to Arizona's economy (Beattie and Mortensen 2007). As cities increasingly seek renewable water supplies, however, future groundwater savings transfers to supply agricultural users with CAP water may be limited. Few unallocated renewable water supplies remain, so the increasing water needs for urban areas will require either transfers of water from other uses or new mechanisms to exchange or transfer treated saline water (Holway, Newell, and Rossi 2006). Furthermore, as the marginal value product of water in agriculture is less than that in industrial or municipal uses, many authors anticipate a shift of water from agriculture to these other uses (Colby and Jacobs 2007; Kohlhoff and Roberts 2007).

Projected increases in agricultural activities outside regulated areas may result in increased use of groundwater to meet irrigation demands, with the associated implications of increased costs for pumping groundwater and conflicts over limited supplies in rural areas. Given that surface water and groundwater supplies currently are managed separately, increasing reliance on both sources may lead to increasing conflict over water rights. Because of limited opportunities for water supply augmentation in Arizona, the role of regulation and economics increasingly will be important in managing the water supply. Managing demand through conservation incentives and assistance programs can make water use more efficient (Eden and Megdal 2006). Alternatively, the reuse of effluent, the only water source that is growing, may decrease demand for freshwater from other sources.

A statewide water plan for municipal and agricultural uses might help guide future application of incentives

and regulations and could address some of the geographical disparities between water sources and water demands (Megdal 2008). Throughout Arizona, there is an emerging focus on long-term water planning, often on a regional basis, and better connections between land use planning and water availability. Pima County has drafted and adopted an amendment to their comprehensive plan that enables the county to consider water availability during the rezoning process for new developments (Pima County 2007). The state recently authorized local governments outside AMAs to consider water adequacy when approving new developments (Arizona Senate 2007). Conservation programs based on best management practices have been extended for the agricultural sector and are now the focus of municipal conservation regulations (Megdal, Smith, and Lien 2008). The policy focus of ADWR's first 25 years has been on AMAs. Now throughout the state, in addition to remaining challenges within the AMAs, there is a need to understand the growing—and often competing—demands for water. A drought preparedness plan has been developed for the state, and ADWR is working actively to assist counties, cities, and water providers to coordinate their drought planning (Arizona Town Hall 2004). Ecosystem water needs are recognized, but Arizona's water management framework does not consider the environment explicitly as a water-using sector (Colby and Jacobs 2007). Rapid population growth, continuing drought, and the impacts of climate change are additional factors making water management in Arizona challenging and careful water planning imperative.

Water Resource Sustainability in Florida

As Florida's population grows, demands on freshwater resources to provide (1) drinking water and residential landscape irrigation for cities and (2) irrigation water for agriculture continue to expand. Simultaneously, there is increasing awareness of the importance of preventing pollution and leaving enough water for natural ecosystem functions. These combined pressures define the need for sustainable water resource management.

Water Resources

Florida is relatively rich in freshwater resources, especially groundwater, and has more available groundwater in aquifers than any other state. The Floridan aquifer, which underlies much of the state and is used for drinking water in Northern and Central Florida, is among the world's most productive aquifers. The principal aquifers of Florida combine to supply drinking water to more than 90% of the state's population. The abundant groundwater emerges as spring water in parts of Florida; of the 78 largest springs in the United States, 33 are in Florida—more than in any other state.

Although the rivers in Florida do not rank among the nation's largest (even Florida's largest rivers—the Apalachicola, the Suwannee, and the St. Johns—have only a fraction of the flow of North American and world rivers), Florida has more than 7,800 lakes (Purdum 2002). The largest of these is Lake Okeechobee, which, after Lake Michigan, is the second largest freshwater lake completely within the conterminous United States. In addition to these larger lakes, Florida has tens of thousands of smaller surface water bodies. The inland surface water bodies in Florida have a combined area of more than 4,633 square miles (fourth highest in the United States), representing 7.7% of the state's land area, the second highest percentage in the United States (U.S. Census 2008).

Users of Water Resources

Florida's water resources provide many services, both to ecosystems and to humans. Humans receive direct benefits from water withdrawn from ecosystems by using it for drinking water or other residential, industrial, or municipal services. In addition, water also provides many benefits to humans when used to support agriculture, primarily through irrigation of crops for food and fiber. Humans also receive other direct benefits from water when it is not withdrawn from ecosystems and left to allow those ecosystems to function. Ecosystem-related recreation, conservation, and tourism have been shown to be extremely important to state and local economies.

Groundwater accounted for more than 90% of water withdrawals for public supply in Florida in 2000 (Marella 2004). Most of the major metropolitan areas of the state (e.g., Miami, Ft. Lauderdale, Orlando, Jacksonville) rely exclusively on groundwater. Tampa is the only major city in the state with a significant reliance on surface water resources: the Hillsborough River supplies approximately 50% of the water for Hillsborough County's 1.2 million residents (Marella 2004). Groundwater also represented about half of the agricultural water withdrawals in 2000 (Marella 2004), with the remainder primarily from large natural water bodies (such as Lake Okeechobee) and associated canal systems.

Florida's population of approximately 18 million people is overwhelmingly urban (94%), but agricultural uses (mostly irrigation) accounted for more than half (53%) of freshwater withdrawals in 2000 (USDA 2008; USGS 2004). An additional 14% of freshwater withdrawals were used for industry, mining, and thermoelectric power generation; the remainder (approximately 30 %) was for public water supply.

Florida agriculture was a $7.8 billion industry in 2005, the ninth largest in the United States, despite the fact that Florida ranked only 26th in land area (FDACS 2007). Florida's agricultural base is diverse, with 10 million acres of farmland evenly distributed between crop, pasture, and forest (USDA 2008). The top five commodities in 2006 in order of production value were greenhouse and nursery horticulture, oranges, sugar cane, bell peppers, and tomatoes, produced at national-scale significance, respectively representing 10, 68, 48, 46, and 24% of U.S. production value (USDA 2008).

Water Management

The 1972 Florida Water Resources Act delegated comprehensive water management authority to five regional water management districts covering the entire state (Hamann 1998). The district boundaries follow surface hydrologic basins, cutting across political boundaries such as counties and cities, facilitating ecosystem-level management. For example, the entire watershed of the greater Everglades ecosystem is within the boundaries of the South Florida Water Management District, but

the Floridan aquifer underlies much of the state and thus lies within multiple Water Management Districts, highlighting the need for cooperation among districts for groundwater management.

Among the many responsibilities of the districts is the permitting of consumptive use to regulate water withdrawals. Permitted water withdrawals are required to be consistent with the public interest and provide a reasonable beneficial use; they are term-limited, with a maximum of 20 years, but usually much less. The effect of water withdrawals on natural systems is a consideration in the permit approval process, and permits for withdrawals that adversely impact the environment can be denied. Criteria for the limit of acceptable environmental impacts caused by water withdrawals are established based on minimum flows and levels in surface waters and aquifers (FDEP 2008).

Surface water and groundwater quality in Florida is regulated by the Florida Department of Environmental Protection (FDEP), by authority of the federal CWA. As in most of the United States, Florida surface water pollution from point sources was effectively decreased by the implementation of the CWA, but the effects of pollutants from nonpoint sources on Florida ecosystems are increasingly of concern (FDEP 2006). The FDEP and water management districts have been developing and implementing TMDLs to protect surface water systems from nonpoint source pollution since the promulgation of the 1999 Florida Watershed Restoration Act pursuant to Section 303(d) of the federal CWA. Total maximum daily loads are intended to approximate the maximum amount of a pollutant that a water body can assimilate without causing violation of water quality standards.

Water Resource Concerns

Florida's population is projected to increase 44%, to 26.5 million, by 2030 (Florida Legislature 2007). The major metropolitan areas of Florida all are projected to see significant population increases during this period, with the largest increase (64%) projected for greater Orlando. By 2025, demand for freshwater in Florida is projected to increase by 30%, or approximately 2 billion gallons per day, to 8.5 billion gallons per day (FDEP 2007b). Public water supply is expected to increase by 49% through the next 20 years, whereas water demand for agriculture is projected to increase by only 6%. Thus, by 2025, public water supply will supplant agriculture as the largest freshwater use category. This transition in water demand from agricultural to public supply is being driven by the rapid conversion of agricultural land to urban uses.

Current mass grading practices in the construction of new residential communities in Florida is very disruptive to the soil in terms of compaction and soil profiles. Current landscaping practice relies on extensive areas of irrigated turf. In 2005, more than 200,000 new homes were built in Florida (along with associated golf courses), creating an ongoing demand for irrigation water and landscaping chemicals. Both in terms of water supply and impacts on water quality, land cover change and increased water demand due to rapid urbanization are major factors affecting Florida's water resources now and may continue to be in the future.

Each day in Florida, 2.7 billion gallons of water are extracted by humans from groundwater and surface water systems, whereas an average of 150 billion gallons of rain falls on the state each day. On a statewide scale, therefore, the amount of water extracted by humans is small compared with the daily renewal from rainfall, and on a statewide scale, it is apparent that water in Florida is abundant. But water resource allocation is a problem of spatial and temporal variability, and although the state has abundant water on aggregate, certain parts of the state do not have enough water locally to support continued large-scale development.

Examples of locations in Florida that rely on importing water from neighboring counties or regions include the Florida Keys, St. Petersburg, Charlotte County, and Sarasota County. In several Florida panhandle counties, increased pumping of groundwater after decades of population growth has resulted in a decline in groundwater levels by as much as 100 feet. In many parts of Florida, notably the Tampa Bay area, increased groundwater pumping has resulted in widespread drying of surface water bodies such as springs, lakes, and wetlands that are interconnected with groundwater systems.

The competition for water between human uses and ecosystem needs has been accelerating in Florida because of unprecedented population growth coupled with increased regulatory protection of natural systems. South Florida provides an example where population and associated land development recently have boomed, and protection and restoration efforts focused on the greater Everglades ecosystem also have increased. Florida's Everglades Forever Act of 1994 concurrently initiated a joint state–federal multibillion-dollar, multidecade restoration effort. As part of this restoration, the South Florida Water Management District in 2007 ruled that future water withdrawals from the Everglades watershed be limited to 2006 consumptive use permit levels (SFWMD 2007). Therefore, as local utilities develop water supply plans for the coming decades, alternative water supply sources not linked to the Everglades must be identified.

Water quality also is a continuing concern for both groundwater and surface water resources in the state. The large-scale Everglades restoration currently underway was catalyzed in part by human-induced degradation of the water quality in this sensitive ecosystem. More broadly, water quality was recently categorized as poor in 50% of Florida's river and stream miles, in 60% of its lake acres (excluding Lake Okeechobee), and in 60% of the square miles of estuaries (FDEP 2006). The purity of many of Florida's spring waters also is threatened by the encroachment of human activities within their surrounding springsheds. Nitrate from surrounding land uses has migrated through aquifers and emerged in steadily increasing concentrations in Florida's spring waters (FDEP 2007a). Elevated nutrient levels are thought to be a causal factor in profuse algal growth at many of Florida's major springs and rivers.

Thirty major surface water bodies in Florida (e.g., Lake Okeechobee, St. Johns River, Tampa Bay, Biscayne Bay) have been prioritized for active water quality management pursuant to Florida's 1987 Surface Water Improvement and Management Act (FDEP 2006). For example, the water quality in Lake Okeechobee has suffered from excessive inputs of nutrients

resulting from human activities within its watershed. A TMDL for phosphorus inputs to Lake Okeechobee was set at 140 metric tons in 2001, but annual loads to the lake have exceeded 400 metric tons for decades (LOPP 2004).

Moving Toward Water Resource Sustainability

The historic definition of resource sustainability has meant resource consumption at a rate that leaves "enough" for "future generations." For water resources, a sustainable rate of consumption commonly is considered to be at or below the renewable supply. In most of Florida, this sustainable rate would imply that water consumption rates should be consistent with the supply available from rainfall, rather than depleting groundwater tables or importing water. Moreover, more modern interpretations of water resource sustainability have imposed the dual constraints of consumption at or below renewable supplies while also leaving enough water for natural ecosystems to function. Perhaps the most current application of sustainability ideals further introduces the goal of ensuring social and economic sustainability.

Water supply sustainability concerns in Florida are, as in many parts of the United States, related to nearly complete allocation of locally or regionally available freshwater. But unlike the case in many other areas, a major constraint on future water withdrawals for human use is the regulatory protection of water for Florida's ecosystems. Therefore, providing sufficient water for future needs must be addressed through consideration of both water supply and water demand.

Two different scales of water demand sustainability problems can be identified. At a global, national, or even state scale, municipal water use is usually a minor factor (often less than 15% of total freshwater use), and significant savings are best optimized in the agricultural and industrial sectors (which combine for more than 60% of freshwater use). For example, in 2000, water-intensive flood irrigation was used on 41% of Florida's 2 million total irrigated acres, a decrease from 57% in 1985 (Marella 2004). Water-efficient microirrigation practices were used on 31% of irrigated land in Florida in 2000. On a state-wide scale, there is room for significant improvement in agricultural water use efficiency.

At a municipal or even regional scale, the household water use habits of millions of consumers can be significant locally—despite relative insignificance at larger scales. Long-term sustainability of water resources at the municipal scale will require adjustments in the water use habits of consumers. Much of the municipally supplied potable water is for outdoor home use, such as irrigation of landscapes (approximately 7% of current demand). Low-flow toilets and showers and similar water-saving techniques are important, but savings obtained are relatively small compared with those available from landscape irrigation, for which Florida households still use one-half of their water. For example, irrigation accounted for 64% of residential water use in a 2003–2005 central Florida study (Haley, Dukes, and Miller 2007). In most instances, especially at the household scale, pristine drinking-quality water was used for this purpose; therefore, suburban Floridians also have significant room for improvement in water use efficiency. Methods to decrease water demand include changes in landscaping practices (such as xeriscaping or use of drought-resistant plants) and expansion of the use of reclaimed water for irrigation.

State support for investment in alternative water supply sources was legislated with the Florida Water Protection and Sustainability Program in 2005. These state funds are to help water suppliers develop alternative water supplies to meet the projected 2025 water demands throughout Florida. As of 2007, this program fostered alternative water supply projects with total construction costs of approximately $2.5 billion (FDEP 2007b). In part because of this program, all Florida's water management districts have identified enough sources and projects to meet the 2025 needs. Reclaimed water and brackish water demineralization are the dominant sources of new water supplies, representing 77% of the water developed by the alternative water supply projects. When completed, these projects are expected to provide 725 million gallons per day of "new" water.

Water Resource Sustainability in the High Plains Aquifer

Introduction

The High Plains region often is associated with the underlying Ogallala Formation and other geological deposits associated with the Ogallala. Collectively called the "High Plains aquifer," water pumped from this system is used widely for crop irrigation and by municipalities and industries. Compared with the region's vast reserves of groundwater, rivers and streams in the region are limited,[1] and residents of the region depend heavily on water drawn from the aquifer.

Lying in a semiarid environment and geologically cut off from replenishment by sources outside the region, natural recharge of the High Plains aquifer is meager. After some 50 years of widespread pumping, groundwater resources in some locations are depleted appreciably.

Background

When describing the High Plains aquifer, a wide variety of terms are used—pebbles, cobbles, boulders; substantial variation in mineral content; unconsolidated; cemented; 1,800 feet thick; thin as a feather; seeds and rootlets; pure sand; mostly gravel; fractured caliche. Composed of various materials deposited during the past 30 million years, the aquifer is complex; largely it includes sediments deposited during the Tertiary period (Brule, Arikaree, and Ogallala Formations) and younger, overlying sediments deposited during the Quaternary period (McGuire et al. 2003).

The High Plains aquifer extends beneath some 174,000 square miles in portions of Texas, Oklahoma, New Mexico, Kansas, Nebraska, South Dakota, Colorado, and Wyoming. The region is predominantly rural. The largest cities (U.S. Census 2007)—Lubbock (pop.

[1] In Nebraska, for example, the long-term average annual flow of streams coming into the state is estimated to be 1.8 MAF. Average annual outflow of all streams is estimated to be 8.2 MAF. By contrast, the statewide estimated volume of ground water in storage is 2 billion acre feet (admittedly includes small quantities contained in other aquifers) (UNCSD 1998).

212,200), Amarillo (pop. 185,500), and Midland (pop. 102,100)—are located in Texas. Ironically, Wichita, Kansas (pop. 358,000) does not overlie the High Plains aquifer. To serve a portion of its municipal demand, however, Wichita water wells draw from the Equus Beds, an eastern Kansas unit of the High Plains aquifer (Galloway et al. 2003).

Climatologists classify the High Plains as semiarid. Precipitation and temperature values vary widely, and both locally and across extensive areas, prolonged drought and periods of abnormally abundant precipitation are common. The near decade-long 1930s drought and attendant economic depression in the Oklahoma panhandle and adjoining locations was especially devastating. Going beyond instrumental records and assessing evidence of precipitation during the past 700–800 years, several researchers cite analyses of ancient lakebed sediments and tree-ring data to assert the twentieth century was abnormally wet (Fritz 2005).

In contrast to surface water supplies that are replenished after rainfall and snow-melt runoff events, water contained in the High Plains aquifer is sometimes referred to by geologists as "fossil water." Either as precipitation percolating downward from the land surface or as stream flow from origins lying to the west, most of the water arrived throughout millions of years simultaneous to the deposition of the sediments that now make up the aquifer. With several notable exceptions (e.g., Sandhills area of Nebraska), rates of recharge in most locations are meager. Beneath the eight-state region, the volume of water contained in buried rock fractures and between particles of sand, gravel, and other sediments is nine times the volume of Lake Erie (Ashworth 2006), "approximately equal" to Lake Huron (McGuire et al. 2003).

As a whole, the High Plains aquifer is not polluted. Exceptions are local and exist in areas where chemicals or other pollutants have seeped into the aquifer. Across the eight-state region, 17 "Superfund" sites have been designated to clean up contamination caused by spills and improper disposal of solvents and other compounds (Ashworth 2006). Contamination from animal waste, pesticides, and fertilizers generally is limited to areas where soils are course textured and where elevation of the water table is near the land surface. Because these sites are related to naturally occurring mineral sources, well construction peculiarities, and immoderate rates of pumping, researchers believe high arsenic and uranium concentrations detected in the water supplies of several municipalities may be avoidable (Gosselin et al. 2006).

On the land surface, the High Plains region is drained by the Cimarron, Arkansas, Republican, Platte, and Canadian rivers. Provided their flows are not completely lost to evaporation, consumption, or other causes, High Plains rivers ultimately discharge into the Gulf of Mexico. Flows of most streams vary in response and in proportion to local meteorological events. The headwaters of several rivers (e.g., Arkansas and Platte), however, are located in the Rocky Mountains, where prolonged cold temperatures usually delay snowmelt runoff until May and June.

In some locations, stream valleys are eroded deeply into the landscape; the beds and banks of such streams physically intersect the High Plains aquifer. Where elevation of the water table is above that of the bed, groundwater moves slowly toward and into the stream. The uniform-flowing Dismal River, located in the Sandhills region of central Nebraska, for example, is a recipient of little overland runoff, and nearly all its flow comes from springs and seeps emitting from the High Plains aquifer. Where the stream bed elevation is above the water table, in contrast, flow diminishes as water percolates downward to recharge the aquifer. Adding to the hydrological complexity of the High Plains region, in some locations both situations occur (e.g., Platte River valley).

Water Uses and Impacts

Before World War I, only a few innovative and progressive farm operators pumped irrigation supplies from the High Plains aquifer—early wells were shallow, less than 50 feet deep. Extensive well-drilling began in the 1950s; the initial surge in drilling deep wells began in Texas, where construction of more than 34,000 wells was reported between 1950 and 1959 in the High Plains region (Bittinger and Green 1980). During the same time period, slightly more than half that number were constructed throughout Nebraska (UNCSD 1998).

Probably the result of logistical challenges inherent in locating and counting every water well in the region, no one has undertaken the task. With more than 90,000 irrigation wells officially registered in Nebraska, however, it is logical to conclude that several hundred thousand wells draw water from the High Plains aquifer.

A variety of actions led to development of the High Plains aquifer; of fundamental importance were early test drilling and subsurface exploration activities. Comprehensive investigations undertaken cooperatively by several state geological surveys (especially Kansas and Nebraska) and the U.S. Geological Survey (USGS) are noteworthy. Other exploration programs were supported by lending institutions, electric and natural gas providers, and water well contractors.

Most water consumed in the High Plains region is for irrigation of corn, cotton, soybeans, sugar beets, alfalfa, and other crops. Substantially smaller quantities are consumed by industries, municipalities, and other users; these quantities are not expected to displace amounts used for crop irrigation, barring fundamental changes in the region's economic environment.

With time, the number of irrigated acres has grown considerably—fewer than 2.5 million in 1949, approximately 6.2 million in 1959, 10.5 million in 1974, 13.9 million in 1997, and 12.7 million in 2002 (McGuire 2007). Nebraska and Texas lead all other states with 6.5 million and 3.8 million acres, respectively. Many observers point to substantial increases in production of ethanol and a favorable market for corn as reasons to expect future increases in pumped amounts and in the number of irrigated acres.

Data-gathering activities undertaken by a variety of public agencies and the USGS have documented the effects of pumping. Although not uniformly widespread, results of those efforts generally depict substantial groundwater overdraft in a variety of locations.

During the "Predevelopment to

2005" time period, declines exceeding 100–150 feet were experienced in portions or all of several counties in Texas, Oklahoma, and Kansas (Figure 6). Elsewhere in Colorado and Nebraska, overdraft resulted in declines exceeding 25 feet. Contrary to those trends, in scattered locations in Nebraska (mostly) and in several other states, groundwater levels rose slightly. Overall, since widespread irrigation began in the 1950s, an estimated 6% (McGuire et al. 2003) to 11% (Ashworth 2006) of the original volume of water contained in the aquifer was extracted.

Pumping by large numbers of wells has impacted flows in some watersheds. The Frenchman River, which begins in northeast Colorado, one of several examples (Jess 2005), is eroded into the High Plains aquifer, and its channel traverses eastward across three Nebraska counties. The accumulation of contributions from numerous springs and seeps emanating from the High Plains aquifer make up the Frenchman's baseflow.

Soon after irrigation development in the watershed began in the mid-1960s, local groundwater levels began to drop. Concurrently, baseflow of the river diminished, and the so-called "nickpoint" (location where perennial flow begins) now lies in Nebraska, some 20 miles downstream from where it was located originally. Statistically, the past 40-year average annual flow of the Frenchman River has diminished more than 60%.

Hesitation to Adopt Water Use Regulations

Depletion of groundwater supplies in the High Plains region often invites comparison with oil and gas exploitation. Both are tremendous natural resources formed in geological time, and both groundwater and oil/gas have created substantial wealth for individuals and for society generally. But the parallel between groundwater and oil/gas may be nearing an end. The market for petroleum products is great, and it spurs investment in exploration, recovery, and transportation, but the same market forces also prompt investment into research and development of alternative energy sources.

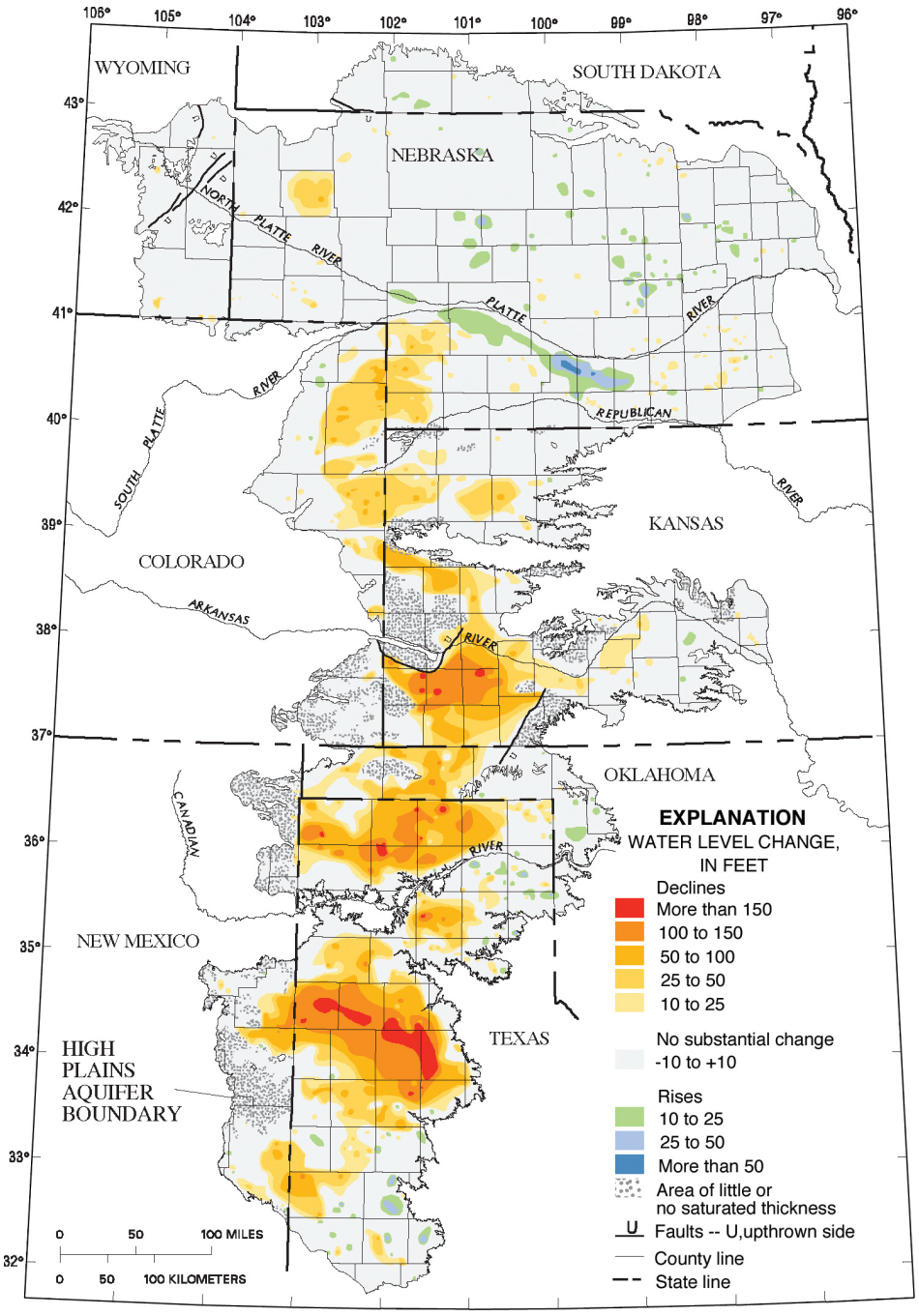

Figure 6. High Plains aquifer, predevelopment to 2005 (McGuire 2007).

Targeted for significant investment in facilities to produce fuel from corn and soybeans, the High Plains region is fortunate. But even if creating fuel from switchgrass or other plants proves successful in boosting production, growing those crops in the High Plains region will remain dependent on irrigation water pumped from the aquifer.

There is no substitute for water. Compared with possible sources for energy, future alternatives for High Plains water use are not plentiful, nor do any of the ambitious schemes for importing water from the Missouri River or elsewhere (Bittinger and Green 1980) seem feasible. Therefore, when discussion turns to the future, it is simply agreed that "something" needs to be done. Other than generally resisting suggestions for

greater federal regulation,[2] "something" has not been defined universally.

Emerging Public Policies

With increased demand for production of food and fiber for a growing population, water undoubtedly will continue to be pumped from the aquifer. Overdraft will not be reversed, and water table declines will expand in aerial extent. For individuals, costs for construction of wells and for pumping will increase.

Societal impacts are discernible and often hotly debated. In western Texas, local residents were reportedly dismayed concerning proposals by T. Boone Pickens to pump High Plains groundwater for transport to El Paso, Dallas–Ft. Worth, and other distant cities (Eller 2003). In Nebraska and several adjoining states, court actions and legislative initiatives are being used to seek relief and gain long-term security.

In conjunction with obligations specified in the Republican River Compact, the State of Kansas initiated litigation against the State of Nebraska and the State of Colorado in 1998. Rather than going to trial, the parties agreed to a formal settlement four years later. Among other things, upstream Nebraska agreed to impose a moratorium prohibiting further construction of large-capacity wells. In addition, both Nebraska and Colorado agreed to restrict amounts consumed on irrigated farms in the watershed.[3]

Although the issue doesn't extend beyond state lines or involve state or federal agencies, indications from the High Plains region are that irrigators and other water users increasingly are at odds concerning the impacts that well water pumping is having on the flow of streams. The Pumpkinseed Creek watershed in western Nebraska is an example. There, an ongoing civil suit initiated by the Spear T Ranch alleges diminution of stream flows resulted from operation of several hundred large-capacity irrigation wells lying upstream from its canal diversion works.

As the twenty-first century began, the Republican River and Pumpkinseed Creek litigation and persistent drought across much of Nebraska called public attention to physical limitations of the state's water resources. In response, a blue ribbon gubernatorial task force was appointed. Its members spent 18 months in study, negotiation, and drafting a comprehensive set of recommendations. Without significant modification, recommendations of the task force were adopted by the Legislature in 2004. Termed a "proactive approach," the legislation (LB 962)[4] directs the Department of Natural Resources to complete regional hydrological examinations. The annual evaluations are to address "expected long-term availability of hydrologically connected water supplies for both existing and new surface water uses and existing and new groundwater uses." In the vernacular of the new legislation, the hydrological assessments are intended to identify whether river basins or stream reaches are "fully or overappropriated."

Less than 4 months after LB 962 was enacted, the director of natural resources declared a large portion of the Platte River watershed "overappropriated." The formal ruling indicated authorized demands routinely exceed the extent of sustainable supplies. The geographical area encompassed by that ruling was immediately closed to approval of new surface water diversions, to new reservoir impoundments, and to construction of new large-capacity water wells.

Shortly afterward, the director also declared all or large portions of several other watersheds were "fully appropriated." In those locations, additional stream flow diversions, reservoir impoundments, and construction of additional large-capacity wells were prohibited until after adoption of Integrated Management Plans prepared by the Department and local Natural Resources Districts.

Reflections

In more than 50 years since use of the High Plains aquifer shifted into high gear, residents have embraced center-pivot sprinklers, soil moisture blocks, eco-fallow cultivation practices, and many other innovations intended to decrease irrigation pumping and increase efficiency. Beginning with New Mexico in 1931, public officials have adopted a variety of initiatives—local districts charged with groundwater management responsibilities, cost-sharing incentives, special taxing authorities, unique regulations—aimed at achieving those objectives.

When reflecting on the implications of diminished flows in streams such as the Frenchman River and the geographic extent of vertical overdraft, however, it is reasonable to wonder if investment in efficiencies and adoption of new public policies truly was effective. Indeed, Ashworth's sobering observation (2006) seems profound: "Groundwater overdraft is not an accident here; it is a way of life. But because it means that water will someday disappear, it is also a way of death."

But, as Ashworth (2006) was quick to point out, it would "be wrong" to take that sentiment and demand an immediate end to irrigation from the High Plains aquifer. Whereas deliberately bypassing the opportunity to divert overland runoff in Kansas' Wet Walnut Creek watershed or the Platte River basin might be expected to benefit particular ecological systems, in most other High Plains locations no utility would be gained from leaving water in the ground. Pumping the ground water has and will continue to create wealth—not only for individuals, local economies, and the states, but for the Nation.

Conclusions and Recommendations

These case studies illustrate the wide diversity in availability, distribution, consumption, and regulation of surface and groundwater resources. Each state or region increasingly is con-

[2] Notwithstanding existence of state requirements, pursuant to the reserved rights doctrine first articulated in *Winters v U.S.*, 207 U.S. 564 (1908), federal agencies and Native American tribes are entitled to sufficient water to fulfill the purpose for which designated lands were formally reserved (Getches 1997). In all, some 2.5 million acres of federal reserved and 1.9 million acres of Indian reservation land overlie the High Plains aquifer (McGuire et al. 2003).

[3] Kansas subsequently asserted Nebraska officials had not satisfactorily fulfilled that obligation. Corresponding to 2005 and 2006, Kansas' Chief Engineer demanded payment of some $72.3 million (included punitive damages). As this publication went to press, that claim was being disputed, and the states had not resolved their latest disagreement.

[4] Later codified as Section 46-713, NRS 1943 (Cum Supp).

cerned with the ability to meet future demand from diverse users. Although the proportion of available freshwater used in agriculture varies widely among the case studies, it is a major proportion of total water use in every area. The California case study highlights the increasing responsibilities being placed on agricultural water users at a time when water resources available to agriculture are being squeezed. Water quality considerations factor into water supply availability.

In California and Florida, environmental water needs are being considered explicitly. In semiarid Arizona, increasing municipal demands for water have many areas of the state looking for additional supplies; urban water use is replacing agricultural water use. Except for the High Plains, water demand by nonagricultural users is increasing, whereas in most areas the available supply for consumptive use is either stable or declining because of climate change, aquifer depletion, or environmental needs. The combination of limited water supply coupled with increasing industrial and residential water use will limit the water available to agriculture in the future.

There will continue to be voluntary decreases in agricultural activity resulting from decreases in cultivated acres as lands urbanize. Voluntary transactions that decrease cultivated acres also are likely—whether temporary to address dry year conditions or more long-term (such as the water transactions that have occurred in Southern California). In addition, there may be regulatory-induced decreases in water resource availability, which may or may not be related to climatic conditions. For example, a declaration of shortage on the Colorado River by the U.S. Secretary of the Interior is expected to first impact deliveries to non-Indian agricultural water users in Central Arizona.

It is important that the impacts of these changes be analyzed and communicated. Some decreases in agricultural activity, such as when cropland is converted to subdivisions, are largely irreversible. Decreases in food crop production will threaten the security of U.S. food supply and the U.S. trade balance. Maintaining near-current levels of agricultural production will require a number of actions, potentially including aggressive enhancements in water use efficiency for all users and expansion of uses of some water supplies, such as effluent waters (where feasible). Expansion of surface and groundwater storage may be required in some areas. In the unique High Plains region, where water demand is met predominately through an essentially nonrenewable aquifer, supplying future water demand requires continued efforts at enhancing water use efficiency. Because those demands cannot be met indefinitely, difficult social and economic transitions and tradeoffs may lie ahead.

This paper identified a variety of emerging conflicts over water use in these four regions, indicating the need for forums for local and regional consideration of tradeoffs between water using sectors. In Arizona, the state Department of Water Resources is working to assist local governments in coordinating drought management plans and in developing local water conservation regulations. California legislation now requires development of integrated water resources management plans by local and regional agencies, which address surface water and groundwater quality and distribution of supplies among urban, agricultural, and environmental needs. Despite planning successes in some regions, policymaking regarding the allocation of water resources between competing sectors should be addressed with stakeholder involvement at a higher level than is currently practiced, through statewide or regional water planning. Additionally, in places where extreme disparities exist in the geography and timing of water supplies relative to water needs, regional and statewide planning efforts must include consideration of water storage measures.

Even with efforts to increase the efficiency of water use and promote expanded reuse of wastewater, it seems likely that agriculture faces a future with less water available. The United States contributes more world food aid than any other nation, but as world and national demand for food and fiber increases with population growth, maintaining this role will be a major challenge. It will require substantial efforts in making irrigated agriculture more efficient.

Even though groundwater management is a state responsibility, few states are "islands unto themselves" when it comes to water resources management. The reliability of water quantity and quality deserves the attention of all levels of government, and private and public sector leadership will be critical. Food and fiber production in the United States clearly are of national and international importance. Because of the relationship among water quality, the quantity of water that can be put to alternative uses, and the interstate reach of many natural and constructed water supply systems, federal involvement in the resolution of long-range water supply issues will be critically important.

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