Water Linkages beyond the Farm Gate: Implications for Agriculture

By Bonnie G. Colby

This article provides an overview of water scarcity challenges in economic sectors beyond the farm gate that may affect agricultural water access and costs. The relative importance of other large, water-using sectors varies by region but includes municipal, energy and industrial uses. Energy-intensive sectors in particular need careful consideration due to the water consumption embedded in energy use.

Changes in water demand in other large water-using sectors can affect agricultural water access and water costs. Analyses of competition for agricultural water need to consider not only physical availability and use patterns, but also water costs to users in the form of price paid per unit (if any), pumping, conveyance and treatment costs, and other charges related to water use. Climate change alters both water demand and supply through changes in precipitation, timing and quantity of runoff, and temperature effects. As a result, examining past use patterns and availability is instructive but not predictive of future patterns.

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Changes in water costs can have a significant effect on regional water use patterns. Responsiveness to changes in costs varies across regions and sectors. Water prices and other costs paid by water users often are not under the direct control of policymakers and can be politically difficult to alter. However, well-functioning water markets send a signal of water's value to water users, which facilitates voluntary trading and helps regional economies adapt to scarcity.

Incentive-based agreements to trade water, money, and exposure to risks of shortage play a crucial role in implementing and paying for regional adaptation to drought and climate change. Such agreements mitigate high costs, conflict, and uncertainty over scarce water. The agricultural sector, the largest water-consuming sector in most regions of the world, can play a leadership role in regional adaptation to scarcity. A proactive stance will not only make the agricultural sector more resilient but also help buffer regional economies from disruptions linked to water scarcity.

Section I explores water use and scarcity. Section II considers competition for water across sectors. Section III outlines adaptation mechanisms to water scarcity. Section IV discusses potential effects on the farm sector.

I. Water Use and Scarcity

Climate change alters water demand and supply through numerous mechanisms and has differing effects in different regions (IPCC; Dettinger, Udall, and Georgakakos). Future demand and supply patterns cannot reliably be projected based on past data. Nevertheless, examining data on water use trends provides a starting point for considering adaptation to an uncertain future.

Water use data—withdrawals versus consumptive use

In examining water use among sectors and considering competition for water, it is important to distinguish between water withdrawn for a particular use and water consumptively used. Water consumptively used is no longer available in the watershed in which the use is occurring because it has been evapo-transpired or otherwise made unavailable for reuse.

The figures in this article refer to withdrawals, because that is the only data available over a series of years at global and national scales.[1] Water withdrawals data are useful to an extent, but do not provide a clear picture of the effects of one sector's water use on other sectors. Much of the water withdrawn for household use and for some industrial uses (such as power plant cooling) returns to streams and aquifers and is used again multiple times. When farmers irrigate crops, a portion of the water removed from rivers and aquifers is "consumptively used" (evaporated or taken up by plants) and no longer available for other nearby uses. The portion of irrigation water that is not consumptively used (called return flows) seeps back into surface and groundwater at varying rates and becomes available for reuse (Brauman).

Figures on consumptive use would provide a more accurate picture of "water use" by sector than data on withdrawals, particularly in assessing the effects of water conservation efforts. "Conservation" by cities, farms, and industries does not necessarily reduce consumptive use and "save" water for other uses. The effect of various water conservation practices on consumptive use needs to be evaluated on a case-by-case basis. Figure 1 illustrates this principle. Water-saving devices and practices can reduce the amount of water withdrawn without changing the amount consumed and without improving downstream flow levels (Brauman).

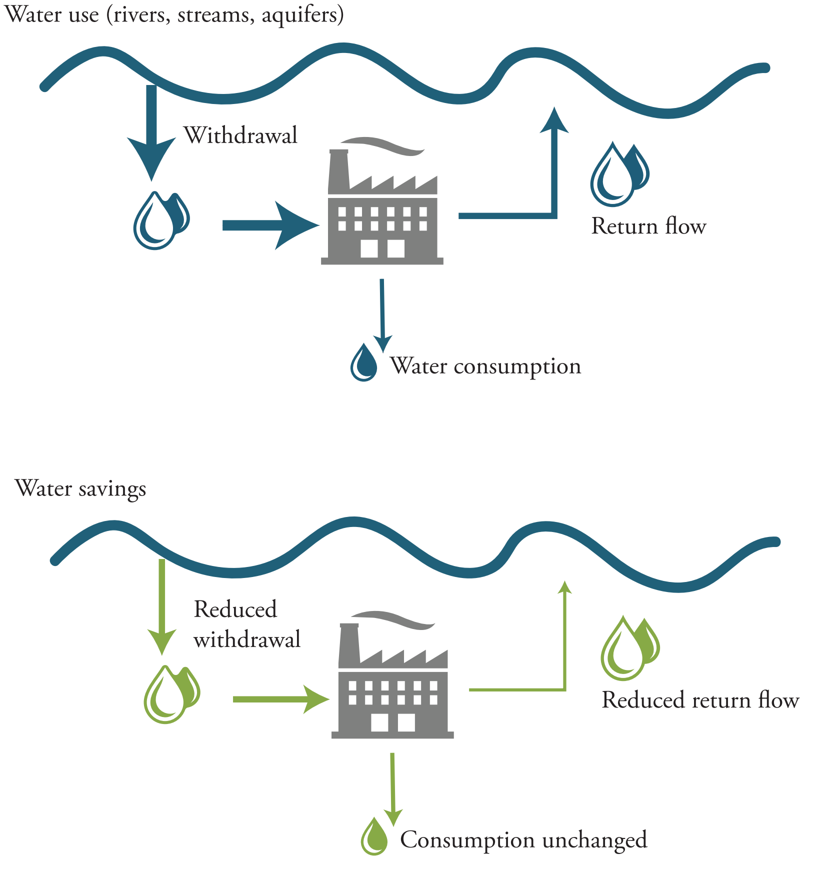
Water withdrawals by sector

Globally and within the United States, water withdrawals for crop irrigation far exceed water withdrawals for industrial and municipal purposes. This is the case for every continent except Europe, where water withdrawals for industry exceed those for agriculture (Maupin and others; FAO 2014). Figures 2 and 3 show water withdrawals by category for the world and for the United States.

Map 1 shows Federal Reserve Districts, which include multiple states. Figures 4 and 5 show water withdrawals by category in two western Federal Reserve Districts. The proportion of urban water withdrawals is much higher in the westernmost Twelfth District, which includes highly urbanized states such as California and Arizona, than in the midwestern Tenth District. Agricultural withdrawals account for the vast majority of water withdrawals in Arizona and California, even though 90 percent of the population lives in urban areas and most of the states' economic activity occurs outside of the agricultural sector.

Figure 1

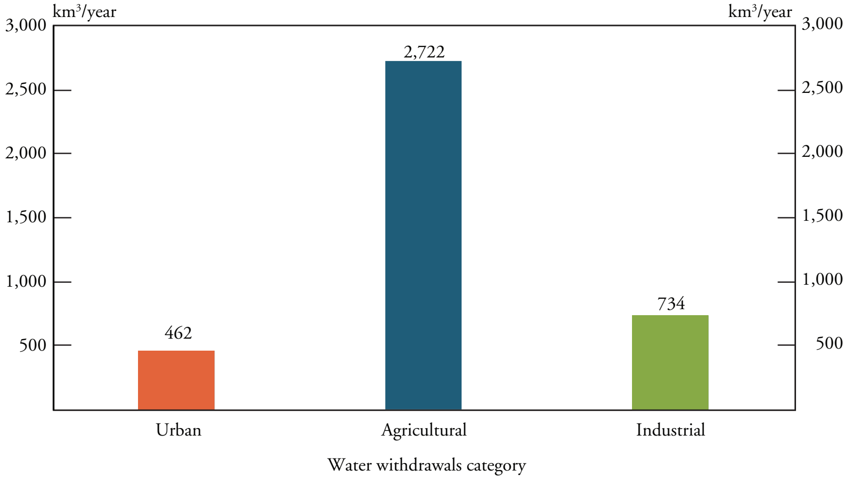
Water-Saving Devices and Practices May Not Reduce Consumptive Use

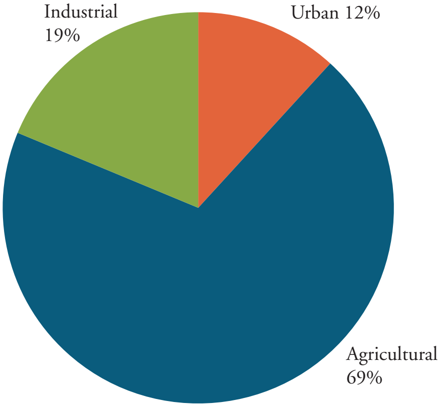


Note: Graphic adapted from Brauman.

Figure 2

Withdrawals by Category in the World, 2007

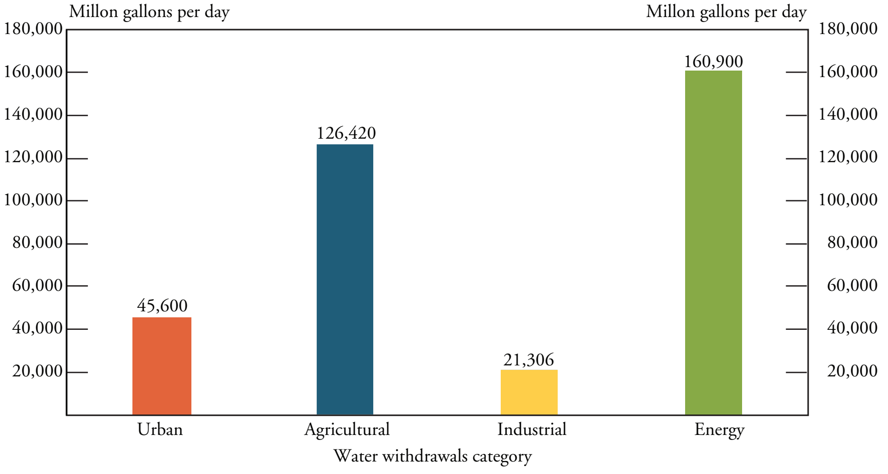


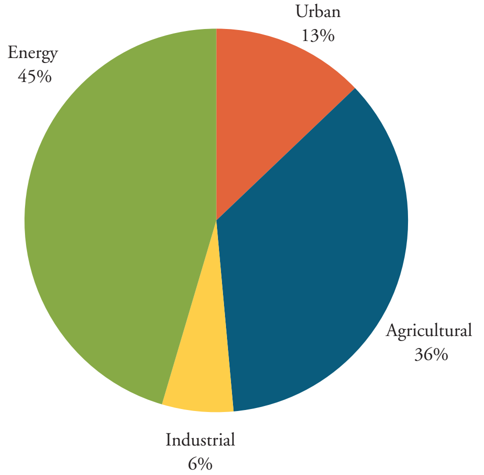


Source: FAO 2014.

Figure 3

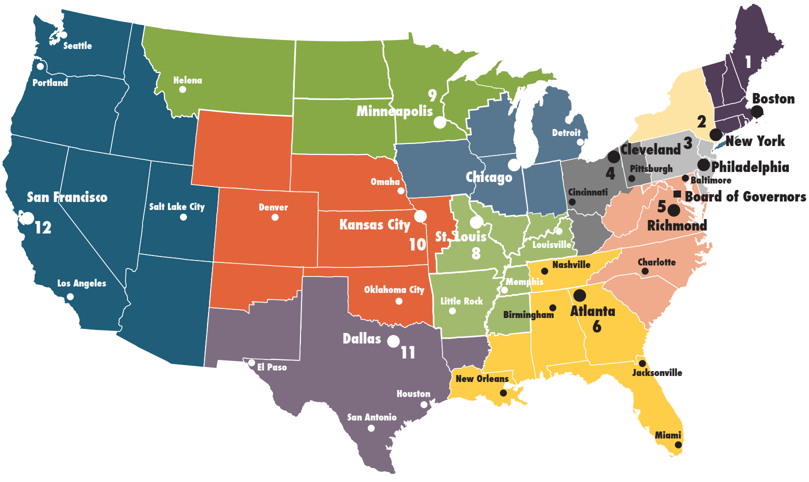
Withdrawals by Category in the United States, 2010





Source: FAO 2014.

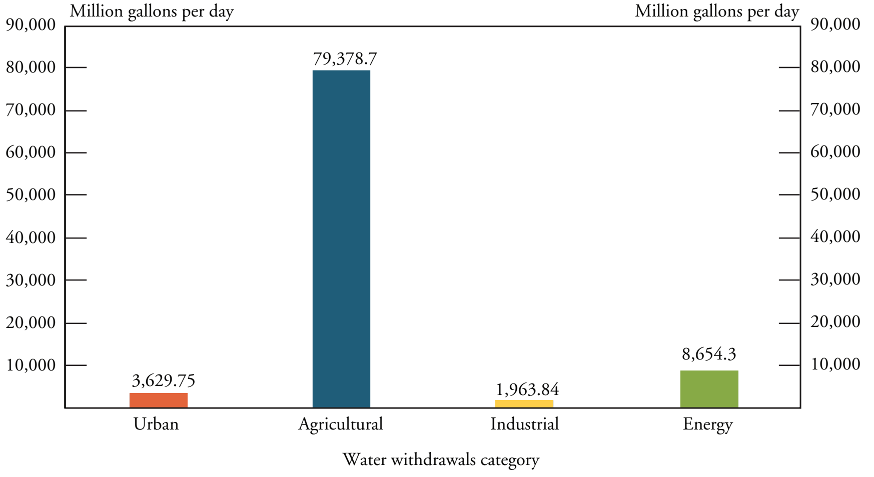
Map1
Federal Reserve District Map

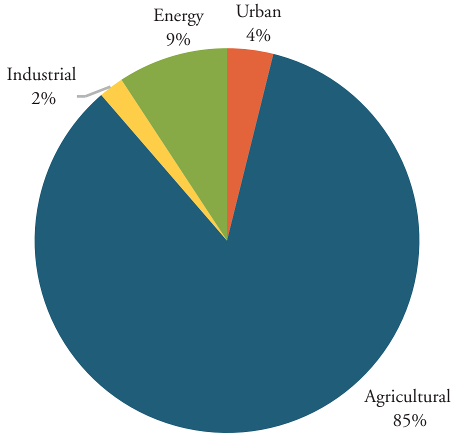


Source: Board of Governors of the Federal Reserve System.

Figure 4

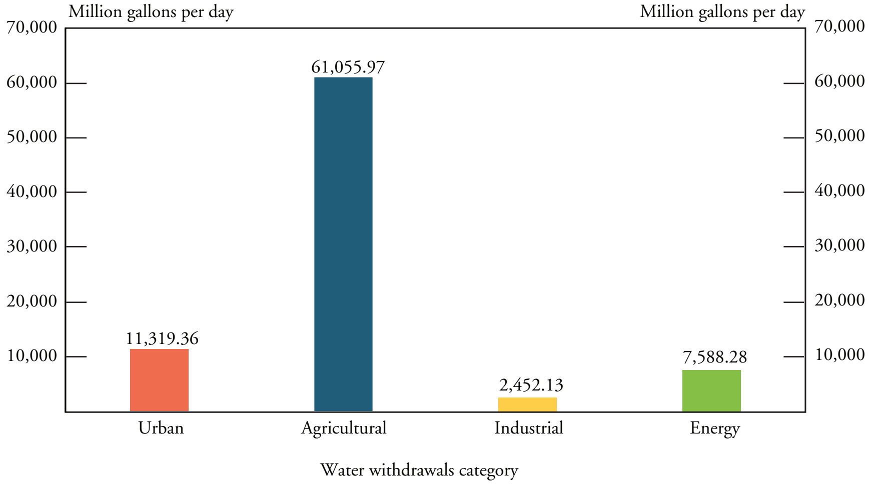
Withdrawals by Category in the Tenth District, 2010

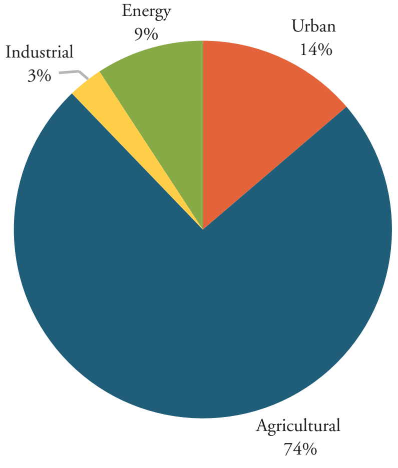




Source: Maupin and others.

Figure 5
Withdrawals by Category in the Twelfth District, 2010





Source: Maupin and others.

Chart 1 shows global water withdrawal data by category over the period 1900 to 2010 alongside world population. The chart shows the energy sector is a significant source of water withdrawals. However, a high proportion of this sector's withdrawals are for power plant cooling water. Most of this water is returned to the hydrological system; only a small portion is consumptively used. Consequently, the thermoelectric sector has a smaller effect on water availability for other uses than Chart 1 suggests.

Chart 2 shows total water withdrawals within the United States from 1900 to 2010, with per capita use included for reference. The decline in U.S. water use per capita, indicated in Chart 2, is driven by many factors, including changes in per capita municipal and industrial use (shown in Chart 3).

By some measures, the United States has experienced significant increases in economic productivity per unit of water withdrawn over time (Chart 4). Donnelly and Cooley define economic productivity of water as "Gross Domestic Product (GDP) generated per unit of water withdrawn," measured on an annual basis and indicated in Chart 4. This measure has increased steadily and significantly over time, indicating that the United States is producing more GDP per unit of water withdrawn.[2]

II. Competition for Water across Sectors

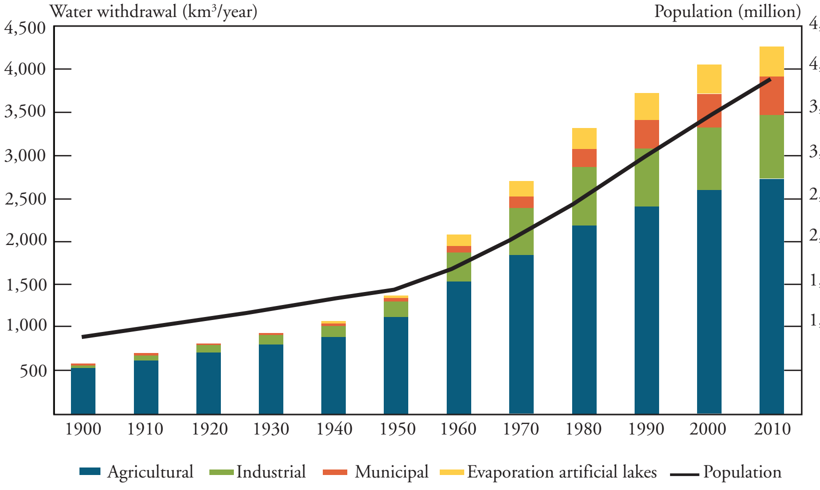
Changes in nonfarm sectors can affect the amount of water available for agriculture, the conditions of its availability, and its cost through multiple pathways. This article considers the urban sector, the energy sector, and other large industrial sectors. These sectors account for the largest water withdrawals (after crop irrigation) globally and in the United States. Changes in water demand or water supply for any of these large water-use sectors have the potential to affect agriculture by increasing regional competition for water.

Another pathway linking water-using sectors involves forward and backward economic linkages through provision of inputs to agriculture and processing of agricultural outputs.[3]

Forward and backward-linked sectors affect agricultural demand for water through their effects on agricultural profitability (for example, changes in the cost of fuel or prices paid by processors to farmers affect farm profitability and thus affect farm demand for water).[4] Moreover, these sectors consume water and so compete directly with farms for

Chart 1

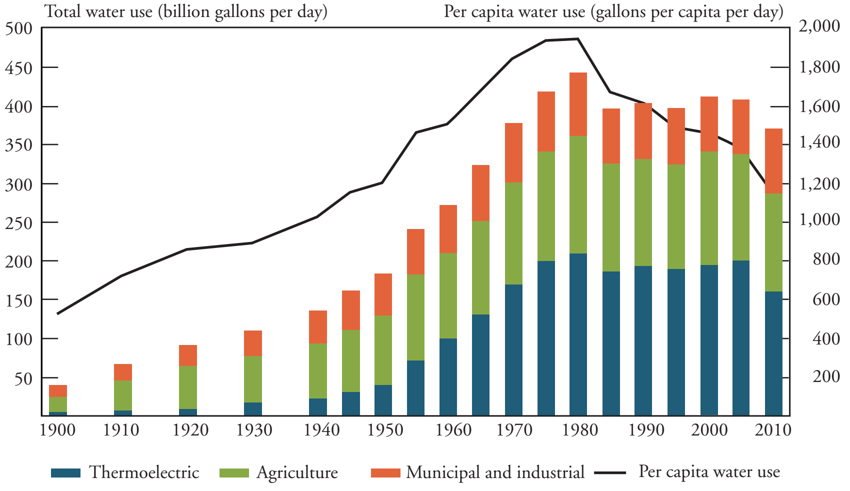
Global Population and Withdrawals by Category, 1900–2010



Source: FAO 2010.

Chart 2

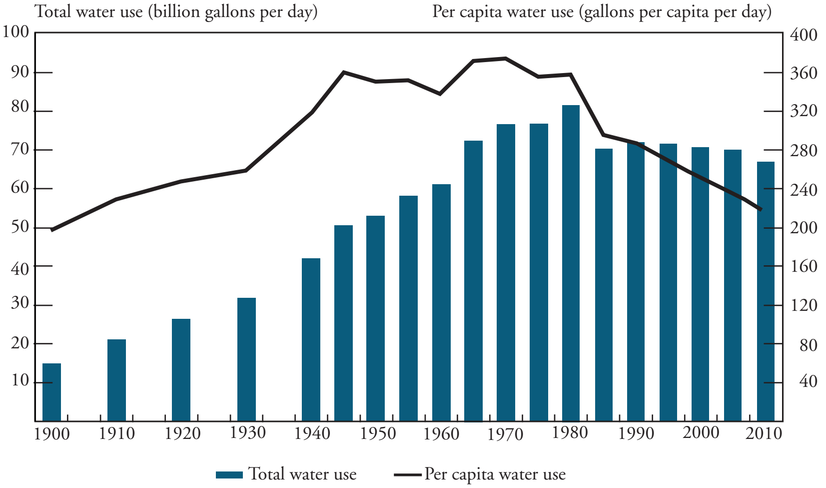
Total Water Use (Freshwater and Saline Water) by Sector, 1900–2010



Notes: Graphic adapted from Donnelly and Cooley. Municipal and industrial (M&I) includes public supply, self-supplied residential, self-supplied industrial, mining, and self-supplied commercial (self-supplied commercial was not calculated in 2000–10). Agriculture includes aquaculture (1985–2010 only), livestock, and irrigation. From 1900 to 1945, the M&I category included water for livestock and dairy.
Sources: Donnelly and Cooley, Council on Environmental Quality, USGS (2014a), and Johnston and Williamson.

Chart 3

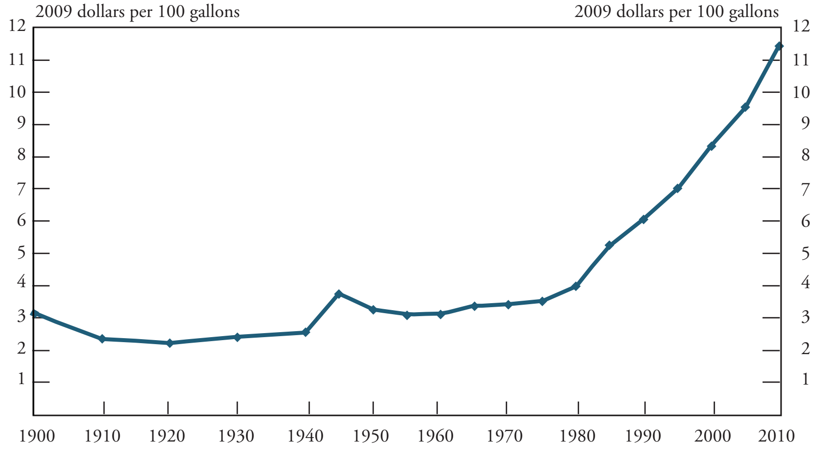
Total and Per Capita Water Use for the Municipal and Industrial Sector, 1900–2010



Notes: Self-supplied commercial water use was not calculated in 2000, 2005, or 2010, which would account for some of the reduction in use that occurred during that period. In addition, the USGS notes that water-use estimates for self-supplied industrial use were more realistic in 1985 than in 1980 and would account for some of the reduction between these years (Solley and others). M&I water use from 1900–45 also includes water for livestock and dairies. Some years include public supply deliveries to thermoelectric; although it was not possible to exclude these deliveries for all years, the years for which data are available suggest this use was relatively small. D.C. was excluded from the analysis due to lack of data.
Sources: Donnelly and Cooley, Council on Environmental Quality, USGS (2014a) and Johnston and Williamson.

Chart 4

Economic Productivity of Water, 1900–2010



Sources: Donnelly and Cooley, Council on Environmental Quality, USGS (2014a) and Johnston and Williamson.

water. These linked sectors consume more water in the same time periods when agricultural water demand is high, thus exacerbating regional competition over limited water.

When agricultural production is more profitable, other factors remaining equal, the value of agricultural water rises and overall agricultural water demand in a region increases. Depending on a region's water allocation mechanisms, higher agricultural demand may cause water prices to rise or conflict over water to escalate. Regional markets in which water can be leased and purchased serve as a "pressure relief valve," providing an alternative to political and legal wrangling over water access.

Economic perspectives on water scarcity, demand, and supply

From an economic perspective, scarcity arises when water is not available to satisfy demand at current costs paid by water users. In common usage, water "demand" refers simply to patterns of water use and "supply" to the physical availability of water. However, when considering competition for water across sectors, it is important to adopt an economic perspective on demand and supply.

Regional water demand functions are temporally and spatially specific, varying across seasons, years, and locations. A demand function indicates how the quantity of water used varies with costs paid by users. The responsiveness of quantity used to cost (price is a component of cost) is measured by "price elasticity of demand." In regions facing reduced supply due to drought, if water costs paid by users do not rise to bring supply and demand back into equilibrium, then excess demand will occur at prevailing prices and other (non-price) allocation mechanisms will be invoked to determine how much water various groups can use. Examples of non-price mechanisms include mandatory curtailment by an administrative agency and legal battles over water access.

Water supply functions capture the relationship between the price water providers receive per unit they supply and the amount of water they supply (price elasticity of supply).[5] The supply function thus conveys changes in the cost per unit of water to those seeking additional water. In regions where growing cities and water-strapped industries look to the agricultural sector to acquire additional water, the net returns per unit of water consumed in growing crops influence the costs other sectors will have to pay to lease and purchase agricultural water (Schuster and others). For example, when hay prices are higher, prices paid to lease water from farmers are higher (Pullen and Colby). Agricultural profitability per unit of water consumed shapes the water supply function for other sectors seeking water from the agriculture sector.

Renewability is an important consideration for a region's water supply. In some locations, precipitation regularly replenishes groundwater. In other regions, such as central Arizona, groundwater reserves were formed eons ago and are not significantly recharged by precipitation. Recent findings indicate that groundwater provides a significant portion of surface flows, estimated at over 50 percent in the Colorado River Basin (Miller and others). Analyses of water scarcity need to consider whether water supplies are renewable or non-renewable.

III. Adaptation Mechanisms to Water Scarcity

Regional adaptations to water scarcity take many forms: altering water rates, facilitating water trading, restricting outdoor water use in cities, mandating conservation practices, and curtailing customary agricultural and industrial uses.

The key role of incentives

While water prices may be the first type of incentive that comes to mind, economic incentives take numerous forms. Some of these incentives are direct and can be used as policy instruments to influence water use—for example, water rates charged to customers of an urban water provider. Other incentives are directly linked to the cost per unit of water used but are not easily altered by policymakers, such as a farmer's cost to pump groundwater from a private well.

Still other incentives operate indirectly. Some of these may be influential but uncertain, such as a potential fine for an irrigation district exceeding its water allotment or a looming court ruling that may impose penalties for failing to provide water for endangered fish. An even more uncertain, yet still influential, set of incentives relates to public values for water to provide recreation opportunities and habitat protection. These values are partially expressed through support for public agency restoration of rivers and wetlands and through successful non-governmental organization (NGO) fundraising for programs that acquire water for environmental needs through leases and purchases and through litigation and lobbying (Water Funder Initiative; Environmental Protection Agency 2015).

To the dismay of economists, water prices charged to urban, agricultural, and industrial water users are not yet widely used as a mechanism to reflect changes in water scarcity. Even when water prices are under the control of municipal policymakers, there is a political reluctance to raise prices for urban water customers.[6] For agricultural and industrial water customers, the costs per unit of water used can be difficult to alter. Water costs paid by farms or industrial users may be based on groundwater pumping and are thus primarily determined by prevailing energy costs. Surface water costs paid by farmers in many areas of the western United States are set under long-term contracts with the Bureau of Reclamation.

In regions where water costs do not vary to reflect changes in demand and supply and where active water trading occurs, signals generated by active water trading are a particularly crucial incentive mechanism. The signal of value transmitted by well-functioning water markets incentivizes water users of all types to consider whether they could reduce their own consumption and earn more by making water available for lease or purchase. Other types of direct incentive signals include rebate programs and cost sharing for water-efficient practices and technologies. In the absence of voluntary reallocation pathways such as rebates and water trading, pressure builds for water-short parties to pursue water access through the courts and administrative processes.

Adaptation mechanisms for urban water use

As Chart 3 indicates, U.S. water use per capita has been dropping since the 1980s due in part to a shift from water-intensive manufacturing to a services sector economy and in part to advances like water-efficient appliances and changes in plumbing codes (Pottinger 2015). However, there is still much room for improvement in outdoor water use, indoor efficiency, water recycling and storm water capture and use. Urban water use per capita is significantly higher in older neighborhoods due to housing with old water-wasting fixtures. Outdoor landscape patterns are changing as programs give homes and businesses incentives to replace lawns with low water use landscaping. In addition, improved measurement and monitoring down to the household use level is growing, though not yet widespread. Smart meters, for example, give households real time information to help adjust their water use in response to incentives.

Although municipal officials are reluctant to raise water rates, many U.S. cities have adopted higher rates and new types of rate structures to generate sufficient revenues to cover their costs in the face of declining per capita use. A recent analysis in California indicates water providers that levy drought surcharges are generally in better financial condition than water agencies that charge flat rates per unit used. The energy sector in California has separated the raw costs of energy itself from the costs of providing energy to customers, and some leaders in the urban water sector are considering how to do this too (Pottinger 2016).

Recycling urban wastewater and capturing and reusing storm water can stretch existing urban supplies. However, capital costs are significant. Loan programs assist in furthering this approach. For example, the California State Water Board facilitates loans for recycled water programs to move the state toward its policy goal of recycling 1 million acre-feet annually by 2020. (Pottinger 2015). Streamlining the permitting process for recycled and storm water projects is another helpful urban adaptation mechanism (PPIC 2015). Referring to Figure 1, it is important to note that not all urban conservation efforts reduce the consumptive use of water in the urban sector and create a net water savings available for other uses. One clear strategy for reducing urban consumptive use is reducing outdoor landscape consumption, a strategy pursued by a growing number of cities that pay households and businesses to remove lawns (Pottinger 2015).

Urban adaptation in the future may include innovative wastewater treatment technologies that generate energy from captured methane to power the water reclamation process as a net zero-energy wastewater treatment system (Pottinger 2016). A zero-energy approach reduces the amount of water consumed in energy production and use.

Smart water-trading platforms are not currently widespread in the United States but can facilitate investment and innovation in water efficiency improvements. For instance, a "smart market" would allow a large industrial user that invests in water recycling (and thus requires less of the high-quality water in their area) to readily lease or sell their "saved water" to other users in the smart market system.

Adaptation mechanisms for industrial and energy sector water use

A large portion of energy used worldwide is consumed capturing, treating, and conveying water to customers and in the course of water use by farms, businesses, and households (Liu and others). In California, the water sector accounts for nearly 20 percent of the state's electricity demand (EI Consultants and Navigant Consulting 2010a and 2010b). Moreover, large amounts of water are consumed in generating energy through electric power plants and petroleum refining. The complex set of feedback between water and energy is sometimes referred to as the water-energy nexus (Fisher and Ackerman). For the purposes of this article, it is sufficient to emphasize that many programs that reduce energy use also reduce water consumption, with specific water savings varying by location and energy conservation practice.

Thermoelectric power plants, the largest withdrawers of water in the United States, use both freshwater and saline water and vary tremendously in the intensity of their water use. An average plant in Arizona uses 0.4 gallons per kilowatt per hour (kWh), while a plant in Rhode Island uses 75 gallons per kWh. The type of cooling system these plants employ determines the difference (Donnelly and Cooley). Overall, the intensity of water use in thermoelectric power production has fallen by over 40 percent in the past three decades. Further improvements can decrease the water withdrawals thermoelectric plants require further. However (harkening to Figure 1), their consumptive use of water will not decrease accordingly and may even increase as higher proportions of power plant withdrawals are used up in the plant cooling process.

Replacing conventional energy sources with renewable energy (wind and solar) has the potential to reduce energy-related water consumption, but this determination needs to be made on a technology and location-specific basis. Moreover, comparisons of water consumption across energy sources need to consider the whole life cycle including construction of facilities and manufacture of equipment, household and business use, and end-of-cycle disposal (Christian-Smith and Wisland).

In addition, hydraulic fracturing ("fracking") to extract oil generates massive demand for water and has become an influential factor in water demand in the regions in which it occurs. Each oil well requires 3 to 5 million gallons of water, and most of this fracking water cannot be reused due to its high salt content. This large, new water demand has caused water trading prices to increase significantly in some regions (Freeman).

Regional water banks and temporary and intermittent water trading

Water banks help ease the effects of water shortages in many areas around the world, including the western United States. Thoughtfully designed water banks provide a way for water users to adapt quickly and cost effectively to changing water supply and economic conditions. Water banks are generally formed through dialogue among stakeholders and water agencies to address specific problems within a well-defined geographic area. Consequently, they typically do not confront the same degree of legal and political obstacles as proposed changes in national or state laws regarding water transfers.

A water bank is a legally authorized entity that facilitates transfers of water on a temporary or intermittent basis through voluntary transactions. Water banks in the United States provide water users with a more reliable water supply during dry years (through voluntary trading) and a means to acquire water when their customary access is curtailed due to regulatory restrictions. In addition, water banks ease the regional economic burden of complying with legal requirements such as interstate compacts or mandatory instream flows for fish and wildlife (Colby 2015). Water banks range in geographic scale from neighboring water users to broad regions that cross state lines (the Arizona Water Bank, for instance, also serves parts of Nevada and California). Water banks in the United States are operated by a wide range of organizations including local, state, and federal government agencies; by NGOs; and by for-profit businesses.

The seasonal and temporary water trading facilitated by a water bank can significantly reduce economic losses due to supply curtailment, thus mitigating the effects of water shortages on regional economies. Specifically, a water bank reduces economic losses that occur when junior rights are curtailed to protect senior entitlements by giving curtailed water users a cost-effective and convenient way to lease water from seniors willing to accept payment for forgoing their water use. Parties enter into water bank transactions voluntarily after weighing the pros and cons. A well-designed water bank makes these arrangements timely and cost effective. Water banks help preserve local water user control and provide choices when external forces such as drought or litigation curtail junior entitlements (Colby 2015).

Water banks can administer various specialized trading arrangements including contingent contracts. Contingent contracts—also called option contracts or dry-year reliability contracts—improve supply reliability for the party paying (the option holder) farmers to fallow cropland under pre-specified shortage conditions. When the contract is triggered, the option holder pays enrolled farmers to temporarily fallow land or to suspend irrigation on land already planted. Some programs pay the irrigation district that supplies water to farmers to cover district-level costs of accommodating a fallowing program. The magnitude, timing, and split of payments between irrigation districts and their member farmers are all determined by negotiations.[7] Contingent contracts are useful in improving supply reliability for junior water users while maintaining a typical agricultural base in average and above-average water supply years. The intermittency of irrigation reductions reduces third-party economic effects as compared with the permanent purchase and retirement of irrigated lands.

Water banks operate in many western U.S states and vary with the regional problems they were created to address. In California, water agencies have actively stored groundwater for local water users for decades to enhance supplies of surface water. Water banking there now also involves storing water underground for more distant parties. Some southern California water banks built up reserves of several million acre-feet, and the large quantities of water they supplied during the drought of the late 2000s dwarfed quantities provided to ameliorate drought effects through other voluntary trading mechanism (Hanak and Stryjewski).

In most U.S. water banks, water is provided through reductions in agricultural consumptive use. Farmers and agricultural districts are key participants in designing and implementing water banks. Native American governments hold quantified senior water rights in many parts of the western United States and participate in water leasing and banking (Colby and others; Thorson and others).

IV. Potential Effects of Competition for Water on Agricultural Water Access and Cost

To recap, competition for water can affect farm water availability and costs. This occurs through multiple pathways, including voluntary trading (with market price signaling changes in water's value) and forced changes in farm water costs and access as a result of administrative and legal processes.

In the United States, legal and political considerations limit the circumstances under which farmers can be required to relinquish water entitlements to make water available for other users. However, court rulings and administrative proceedings sometimes do reduce the amount of water available for on-farm use (McClintock; Zaffos). The pressure for involuntary reallocation intensifies during periods of extended drought and during conflicts over water for endangered species, water quality protection, and reliable urban supplies.

Regional water trading systems provide an important "pressure relief" mechanism to reduce reliance on litigation as a strategy to reduce water available for farming. Policies that provide mechanisms for water to be purchased or leased from farms and irrigation districts and transferred to urban and environmental needs provide an alternative to high-cost and high court battles over water. In some regions, extended litigation and administrative proceedings over water allocation still occur alongside water market transactions. Nevertheless, well-designed water trading mechanisms provide flexible, transparent, and cost-effective ways to move water in response to drought, changing economic circumstances, and special needs.

Regional water trading allows farmers and agricultural districts to benefit directly from rising water values by leasing and selling their water entitlements. They also are exposed to higher costs if they need to enter the market to lease or purchase water. Given that agricultural interests hold large senior entitlements in many areas of the western United States, agricultural entitlement holders will more commonly participate in trading as potential sellers/lessors of a valuable asset rather than as buyers/lessees. The record of water transactions in the western United States demonstrates that agricultural sellers and lessors typically command a price that far exceeds the net returns of on-farm water use (Wichelns; Colby 2015).

Changes in water transaction prices in regions with active markets

Examining past patterns of change in water values indicates how competition for water across sectors can affect agriculture. Statistical analyses of water transaction patterns indicate water demand in other sectors can affect the agricultural sector in several different ways. First, farmers and agricultural districts seeking to lease or purchase water face prices influenced by other sectors. Second, the opportunity cost of water used in agriculture is tied to the prices at which water is traded in regional markets. As market prices signal a higher value per unit of water, farmers with tradable entitlements weigh the returns they can earn from leasing or selling water against the returns they expect to earn growing crops.

Loomis and others examine water market transactions specifically for environmental purposes in the western United States over the period 1995 to 1999. They find that lease values were similar to values estimated for instream flows using non-market valuation techniques and that environmental values exceeded agricultural values for water in specific locations. Brookshire and others analyze statistical patterns in water trading in sub-regions of Arizona, New Mexico, and Colorado. Their econometric analyses find that population change, per capita income, and drought indices have a statistically significant effect on the price at which water is traded, with higher trading prices in drier years.

Bjornlund and Rossini examine the price and quantity of water allocations traded in parts of Victoria, Australia. Results indicate that the most important determinants of water price and volume are seasonal allocation levels, rain, and evaporation. The authors find that irrigators make good use of water markets to manage their variable water supply.

Brown's econometric model of western United States water transactions examines water sales and leases and includes transactions for municipal, urban, or environmental purposes in 14 western states. The results suggest higher lease prices occur in drier time periods, in counties with larger populations, and for municipal and environmental uses. The results for water sales suggest that higher sales prices are related to municipal use, surface water, smaller county populations, and smaller volumes of water traded.

Pullen and Colby's statistical models identify water right seniority and factors influencing agricultural profitability (such as hay prices) as key influences on transaction prices. Jones and Colby analyze hundreds of water leases across four western states (Arizona, California, New Mexico, and Utah) over a 29 year period. Statistically significant variables influencing lease price include per capita income, drier weather, and population growth.

Basta and Colby's econometric models of hundreds of western U.S. water transactions over 1987 to 2010 include urban housing price indices, urban area population, and drought indices. Although each regional model is unique, the urban housing price index is positive and statistically significant in all models. The volume of water involved in a transaction and urban population change is significant in all models as well. While the influence of drought on transaction price varies across areas, drought in the area of a city's water supply origin has a more consistent influence on transaction price than drought in the urban area itself. Hansen, Howitt, and Williams develop econometric models encompassing thousands of western U.S. water sales and leases and find that agricultural production levels and land values influence market activity, as do measures of drought and water supply variability.

Although water trading in the western United States is limited in geographic scope, analyses of areas with several decades of active transactions suggest the potential effect of trading is increased competition for water in agriculture. Drought, changes in urban economic activity, population changes, and changes in farm production and profitability all influence water transaction prices and thus the water value signals transmitted to farmers.

V. Conclusions

This overview article introduces themes raised in the complex interrelationships between agriculture and other water-using sectors and between climate change, the energy-water nexus, water scarcity, and competition and adaptation mechanisms.

The agricultural sector has a unique opportunity to shape adaptation to water scarcity. Taking a position that the best defense is a proactive offense, agricultural organizations and water districts are developing collaborative partnerships and risk-sharing arrangements with other large water users. Farmers and agricultural organizations fruitfully propose and support state and federal policy reforms that establish water banks and other innovative forms of water trading that address agriculture and other sectors' water needs and equitably consider potential effects on third parties (Family Farm Alliance; Colby 2015). Agricultural districts are key players in water banks and other innovative mechanisms to adapt to water scarcity (Marshal and others; Colby 2015). These efforts further water trading as a regional pressure relief valve and reduce the impetus for legal and political maneuvers to curtail agricultural water access.

Endnotes

[1]It is possible to calculate consumptive use by sector for specific regions using detailed region-specific data and models, but this is not within the scope of this overview paper.

[2]GDP has been criticized as a measure of economic output for neglecting to include changes over time in natural capital such as water and air quality and habitat. This indicator of water's economic productivity could usefully be refined (with considerable work) to reflect a broader spectrum of economic considerations and to reflect consumptive use by sector rather than water withdrawals. Nevertheless, this indicator shows significant change over time in patterns related to U.S. economic production and water use.

[3]Backward-linked sectors provide inputs to agriculture such as fertilizer, seed, farm equipment, fuel, and water. Forward-linked sectors purchase crops and livestock and add value to farm outputs through processing and distribution. Examples include cotton gins, feedlots, textile mills, and grain-processing facilities.

[4]Due to the brief and non-technical nature of this article, the focus here is on competition over water rather than on specific forward and backward linkages.

[5]Many water providers cannot provide additional amounts when users' willingness to pay per unit provided increases due to long-term contracts (as with Bureau of Reclamation water projects) and other restrictions. Consequently, a regional water-supply function may appear as a series of upward rising steps with each step representing a quantity of water provided by a specific provider at a specific price to users.

[6]Recently, however, many U.S. cities have had to significantly increase water charges to ensure revenue sufficiency in the face of declining use (Walton).

[7]For examples of these types of arrangements, see O'Donnell and Colby; Colby 2015.

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