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Water Conservation in Irrigated Agriculture: Trends and Challenges in the Face of Emerging Demands

Glenn D. Schaible and Marcel P. Aillery



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Recommended citation format for this publication:

Schaible, Glenn D., and Marcel P. Aillery. *Water Conservation in Irrigated Agriculture: Trends and Challenges in the Face of Emerging Demands*, EIB-99, U.S. Department of Agriculture, Economic Research Service, September 2012.

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United States
Department
of Agriculture

Economic
Information
Bulletin
Number 99

September 2012



A Report from the Economic Research Service

www.ers.usda.gov

Water Conservation in Irrigated Agriculture: Trends and Challenges in the Face of Emerging Demands

Glenn D. Schaible
Marcel P. Aillery

Abstract

This report relies on findings from several national surveys and current literature to assess water resource use and conservation measures within the U.S. irrigated crop sector. U.S. agriculture accounts for 80-90 percent of the Nation's consumptive water use (water lost to the environment by evaporation, crop transpiration, or incorporation into products). Expanding water demands to support population and economic growth, environmental flows (water within wetlands, rivers, and groundwater systems needed to maintain natural ecosystems), and energy-sector growth, combined with Native American water-right claims and supply/demand shifts expected with climate change, will present new challenges for agricultural water use and conservation, particularly for the 17 Western States that account for nearly three-quarters of U.S. irrigated agriculture. Despite technological innovations, at least half of U.S. irrigated cropland acreage is still irrigated with less efficient, traditional irrigation application systems. Sustainability of irrigated agriculture will depend partly on whether producers adopt more efficient irrigation production systems that integrate improved onfarm water management practices with efficient irrigation application systems.

Keywords: agricultural water conservation, irrigated agriculture, irrigation efficiency, water supply and demand, irrigation technologies, water management practices, water conservation policy

Acknowledgments

The authors would like to thank Steve Wallander from USDA's Economic Research Service, Jim Ayars from USDA's Agricultural Research Service, Raymond J. Supalla from the University of Nebraska – Lincoln, Brian Hurd from New Mexico State University, Jan Lewandrowski from USDA's Office of the Chief Economist, and Noel Gollehon from USDA's Natural Resources Conservation Service for their review comments and suggestions. The authors also wish to thank Angela Anderson for editorial support and Curtia Taylor for production/design support.

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Summary

What Is the Issue?

Population and economic growth, changing social values about the importance of water quality and the environment, and Native American water-right claims will continue to drive growing U.S. demand for water resources. Expansion of the U.S. energy sector is expected to further increase regional demands for water. At the same time, projected climate change—through warming temperatures, shifting precipitation patterns, and reduced snowpack—is expected to reduce water supplies and increase water demand across much of the West.

These trends are placing greater pressure on existing water allocations, heightening the importance of water management and conservation for the sustainability of irrigated agriculture. How well irrigated agriculture adapts to growing constraints on water, particularly by increasing its water-use efficiency, will directly affect the economic health and sustainability of the sector.

What Did the Study Find?

Irrigated agriculture, which accounts for 80-90 percent of consumptive water use in the United States, represents a significant share of the value of U.S. agricultural production.

- Based on the 2007 Census of Agriculture, irrigated farms accounted for roughly 40 percent (\$118.5 billion) of the value of U.S. agricultural production; nationwide, the average value of production for an irrigated farm was more than three times the average value for a dryland farm.
- Irrigated farms accounted for 54.5 percent (\$78.3 billion) of the value of all crop products sold and contributed to the farm value of livestock and poultry production through animal forage and feed production. Livestock/poultry products accounted for roughly a third of market sales for irrigated farms and 63 percent for nonirrigated (dryland) farms. Irrigated forage and feed production contributed to the livestock/poultry market sales for both irrigated and nonirrigated farm types.
- Nearly 57 million acres were irrigated across the United States in 2007, or 7.5 percent of all cropland and pastureland. Roughly three-quarters of U.S. irrigated agriculture occurred in the 17 Western States, although irrigation has been expanding in the more humid Eastern States.
- Based on the 2008 Farm and Ranch Irrigation Survey (a followup to the 2007 Census of Agriculture), irrigated agriculture across the Western States applied 74 million acre-feet (24 trillion gallons) of water for crop production, with 52 percent originating from surface-water sources and 48 percent pumped from wells that draw from local and regional aquifers.

Demands on agricultural water supplies are likely to increase over time as alternative nonfarm uses of water continue to grow. Potential Native American water-right claims have been estimated at nearly 46 million acre-feet annually and could impact the distribution and cost of irrigation water in the West. For many States, the scope of water demands for the environment have expanded from a minimum instream flow to an “environmental-flows” standard (i.e., a concept requiring water to meet the needs for water quality, but to also rehabilitate ecosystem habitats). Energy-sector growth is expected to significantly increase water demands for an expanding biofuels sector, utility-scale development of solar power, innovation in thermoelectric generating capacity, and commercial oil-shale and deep shale natural gas development. Expansion in these competing water demands, especially with water supply/demand impacts expected with climate change, presents new challenges for agricultural water use and conservation, particularly in the arid Western States.

While substantial technological innovation has increased the efficiency of irrigated agriculture over the past several decades, significant potential exists for continued improvement. At least half of irrigated cropland acreage across the United States is still irrigated with less efficient, traditional irrigation application systems. In addition, most irrigators do not make use of the more efficient onfarm water-management practices that conserve the most water.

- Irrigators continue to make significant investments in new and improved irrigation systems. Approximately \$2.15 billion was invested in irrigation systems in 2008, a 92-percent increase over investments for 2003.
- Most onfarm irrigation investment is financed privately—less than 10 percent of farms reported financing irrigation improvements in 2008 through public financial assistance programs. Nearly 57 percent of the farms that received financial assistance for irrigation technology adoption did so through USDA’s primary working lands conservation program—the Environmental Quality Incentives Program (EQIP). Irrigated farms participating in EQIP, however, represented only about 4 percent of all farms making irrigation investments in 2008.
- Over time, EQIP funding has had an important impact on irrigation investments, amounting to \$1.4 billion from 2004 through 2010. Nationally, irrigation practices accounted for roughly a quarter of total EQIP funding obligations (\$5.7 billion) during 2004-10.
- Less than 10 percent of irrigated farms use advanced onfarm water management decision tools, such as soil- or plant-moisture sensing devices, commercial irrigation-scheduling services, or computer-based crop-growth simulation models. The sustainability of irrigated agriculture may depend partly on the willingness and ability of producers to adopt irrigation “production systems” that more effectively integrate improved water management practices with efficient irrigation application systems.
- Agricultural water conservation is both a farm and basin-level resource conservation issue. Integrating the use of improved onfarm irrigation efficiency with State and Federal watershed water-management

tools (e.g., conserved water rights, drought water banks, option and contingent water markets, reservoir management, irrigated acreage and groundwater pumping restrictions, and irrigated acreage retirement) encourages producers to recognize and respond to differing values of water across competing uses, improving the potential for sustainable irrigation while facilitating water reallocation to other uses.

How Was the Study Conducted?

This report draws on several USDA agricultural production and water-use analyses and surveys, as well as an extensive literature review, to describe the U.S. irrigated agriculture sector, existing and emerging water demands, trends in water-use efficiency in irrigated agriculture, and funding levels (private and public) for farm-level irrigation investments. USDA's Censuses of Agriculture (1982-2007) and Farm and Ranch Irrigation Surveys (FRIS) for 1984-2008, together with the U.S. Geological Survey's (USGS) water-use summaries, were used to assess the demand for U.S. water resources and the importance of irrigation to U.S. agriculture—where it occurs, what it produces, how much water agriculture uses, the water sources supplying irrigation, and the costs of irrigation. FRIS data are also used to analyze the efficiency of irrigated agriculture as of 2008 to demonstrate the potential for continued agricultural water conservation as producers more effectively integrate onfarm and off-farm water management practices with improved irrigation production systems. USDA's FRIS and conservation program contract data are used to examine the current status of private and public investments in irrigated agriculture.

Introduction

Across the United States, human and environmental demands for water resources have increased significantly over the last 50 years. Population and economic growth, changing social norms regarding the importance of water quality and protection of ecosystems, and longstanding Native American water-right claims have increased pressures on available water supplies, particularly in the arid Western States. Given that agriculture accounts for 80-90 percent of U.S. consumptive water use, relatively fixed water supplies and growing water demands have heightened conflicts over agricultural allocations in water-short years.

Water conflicts have required a variety of legislative and judicial remedies, generally involving reallocation of agricultural water supplies to meet the rising needs of competing water users (NRC, 1996; CBO, 1997; Gollehon and Quinby, 2006; Schaible et al., 2010). Historically, Federal and State programs have focused on agricultural water conservation, mandatory withdrawal restrictions, and the use of water markets to meet the Nation's various water needs. More recently, water demands for an expanding energy sector and shifting regional water balances under climate change projections have heightened awareness of the importance of water conservation for a sustainable future for irrigated agriculture. Knowledge about the status and the social and institutional dimensions of competing uses of water resources provides a better understanding of the supply and demand challenges facing irrigated agriculture.

Water Supply and Demand Challenges for Irrigated Agriculture

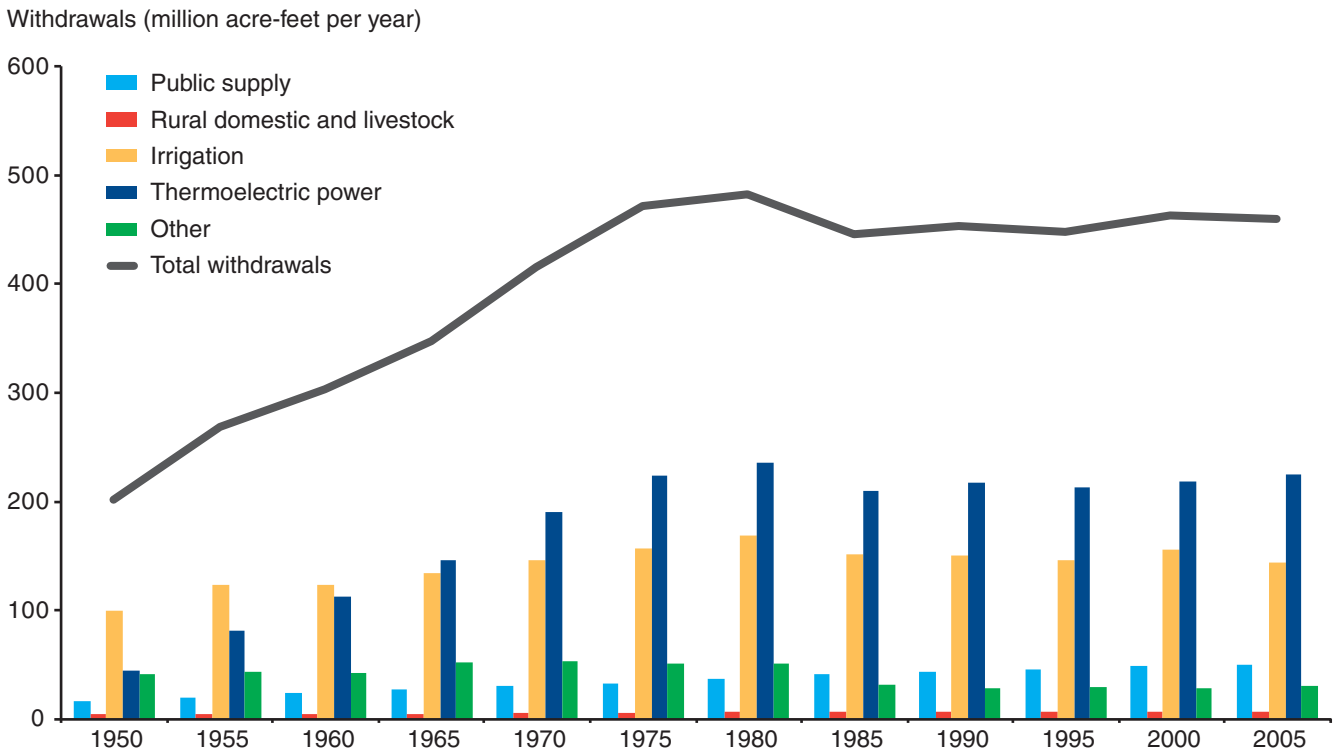
Traditional Water Demands: Agriculture Versus Nonagricultural Sectors

The U.S. Geological Survey (USGS) has developed water-use estimates for major water demand sectors of the United States, reported every 5 years since 1950 (fig. 1). Water withdrawals¹ across all sectors—including public use (largely municipal), rural/domestic use, livestock use, irrigation, thermoelectric power generation, and all other uses—increased dramatically between 1950 and 2005. Total water withdrawals, which peaked at about 482 million acre-feet (maf)² in 1980 before declining slightly and then leveling off after 1985, were estimated at 460 maf in 2005 (or 128 percent higher than in 1950) (Kenny et al., 2009). Water withdrawals for irrigated agriculture and the thermoelectric power sector—traditionally the dominant sources of water demand—have increased the most since 1950. Nationally, water withdrawals for thermoelectric power (primarily for cooling purposes) accounted for 49 percent of total U.S. withdrawals in 2005 (about 225 maf). Thermoelectric withdrawals increased 400 percent between 1950 and 2005, with a 4-percent decrease from peak demand in 1980. Nearly 98 percent of water withdrawals for thermoelectric cooling systems, however, currently return to their source

¹Water withdrawals (one measure of water demand) refer to the removal of water from streams, rivers, lakes, reservoirs, and groundwater aquifers for a specific use.

²An acre-foot of water represents the quantity required to flood 1 acre of land at 1 foot in depth, equivalent to 325,851 gallons.

Figure 1
Trends in total water withdrawals, by major water-use category, 1950-2005



Note: U.S. Geological Survey water use numbers were converted to million acre-feet units.
Source: Kenny et al., table 14, p. 43, 2009.

of origin, where the water can be reused for other purposes, including irrigation.

Irrigated agriculture, with withdrawals of about 143 maf, accounted for 31 percent of the Nation’s total in 2005. Irrigation withdrawals in 2005 were 43 percent above the level for 1950, though 15 percent below peak demand in 1980. For the 17 Western States,³ irrigated agriculture accounted for most water demand from both surface water and groundwater sources (fig. 2) (Kenny et al., 2009). In 2005, water withdrawals for irrigated agriculture in the 17 Western States totaled approximately 122.4 maf, or 64 percent of total water withdrawals in the region; irrigated agriculture accounted for 58 percent of surface water withdrawals and 79 percent of groundwater withdrawals.⁴

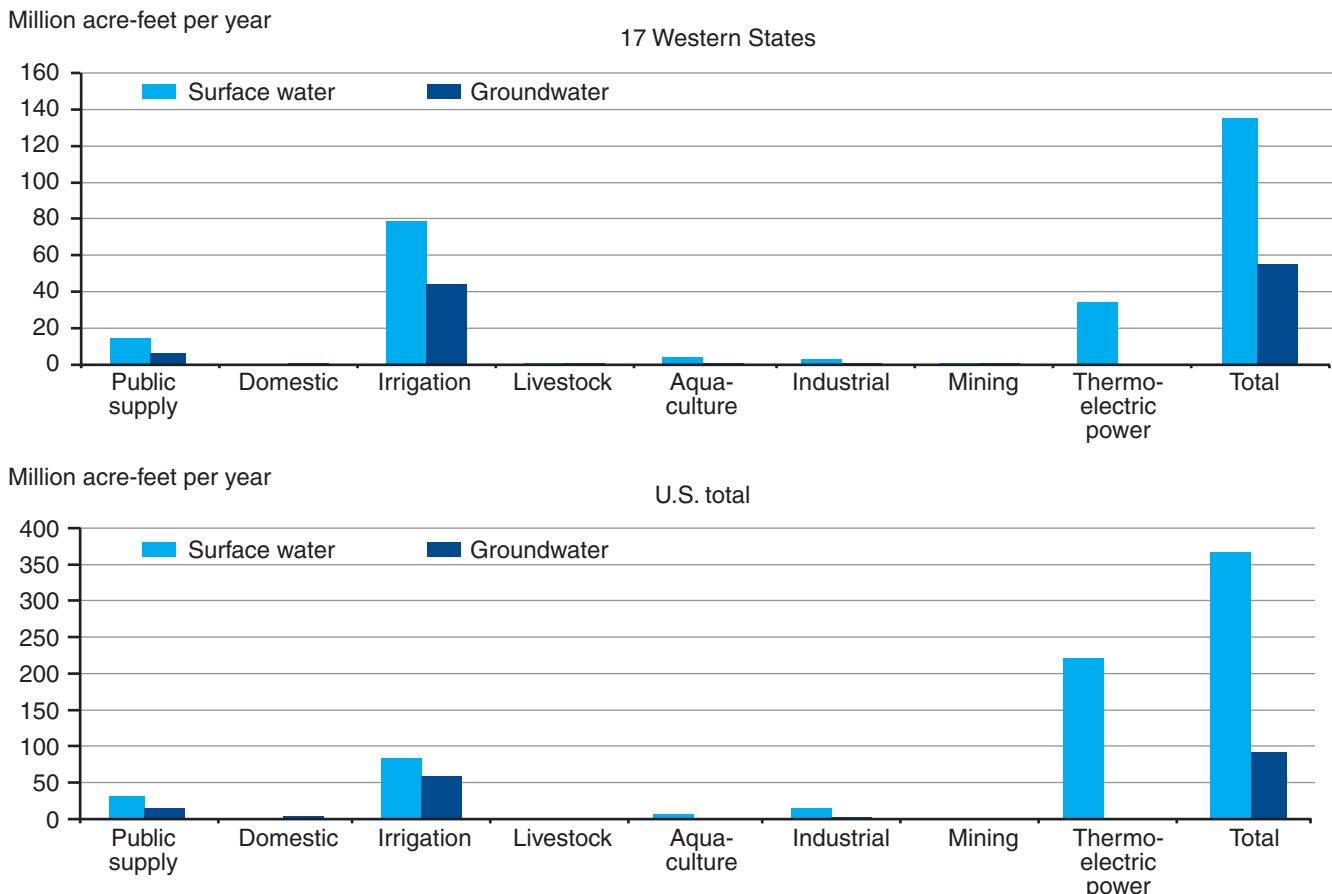
New Challenges for Irrigated Agriculture

Competing demands for U.S. water resources have continued to increase and are expected to intensify water resource conflicts over the foreseeable future. Important sources of expected growth and/or emerging water demands include Native American water rights, instream (environmental) flow

³The 17 Western States include Arizona, California, Colorado, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, South Dakota, Texas, Utah, Washington State, and Wyoming. All other States within the contiguous United States are referred to in this report as the 31 Eastern States (or Eastern States).

⁴Water withdrawals as a measure of water demand are used here because they are the best and most recently available data by water-demand sector. Some portion of withdrawals returns to the hydrologic system, is lost to the system, or is otherwise irrecoverable after its initial use. Consumptive use by sector would provide improved estimates of water demand; however, the most recent USGS water-use estimates do not identify consumptive use values. USGS last estimated consumptive water use by sector in 1995.

Figure 2
Water withdrawals, by water source and water-use category, 2005



Source: USDA, Economic Research Service calculations based on Kenny et al., p. 52, 2009.

requirements, and an expanding energy sector. In addition, climate change is expected to affect both the supply of and demand for freshwater.

Native American Water Rights

Native American reservation water rights were established by the U.S. Supreme Court in its 1908 *Winters v. United States* decision. The ruling established reserved water rights based on the amount of water necessary for Native Americans to maintain and survive on the land granted to the reservation by the Government, even if those rights were not explicitly stated in the reservation treaty. In subsequent decisions, the U.S. Supreme Court quantified those water rights as the water needed to irrigate all “practically irrigable acreage” on the reservation and made such rights generally superior to the rights of all other appropriators by vesting them with a “priority” date equivalent to the date the reservation was established (Gregory, 2008; Moore, 1989). In addition, while *Winters v. United States* applies to surface waters, in 1976, the U.S. Supreme Court (*Cappaert v. United States*) opened the door for Native American reserved water-right claims to apply to groundwater. No definitive decision on Native American reserved groundwater rights has been made, but some States recognize these rights (Gregory, 2008).

Potential Native American water-right claims have been estimated at nearly 46 maf annually (Western States Water Council, 1984). At present, the claims for many reservations are under negotiation or remain unresolved within settlement disputes or judicial proceedings. Future resolution of these water-right claims will undoubtedly affect the water resources available for competing uses, including off-reservation irrigated agriculture. Settling Native American water-right claims, however, may not result in less water for agriculture, but rather a reallocation of existing water rights. While water delivered to U.S. Tribes generally originates from existing water-right allocations, Tribes are generally allowed to assign, exchange, lease, and create options to lease water rights through settlement arrangements. Within existing negotiated settlements, some reallocated water supports irrigation expansion on reservation lands, but Tribes also may agree to lease water to off-reservation agricultural users, to non-Indian lessees on reservation lands, and to nonagricultural users, such as municipalities (Claims Resolution Act of 2010).

To the extent that Tribes accept compensation in lieu of wet water, the actual reallocation of water from existing agricultural users may be limited. However, due to the political and financial challenges in negotiating or adjudicating water rights claims and a lack of ability to finance irrigation projects and related storage, exercising reservation water rights has moved historically at a relatively slow pace. The reality is that, for many reservations, future development of these claims will likely continue to progress slowly barring an infusion of economic, legal, and technical assistance.⁵

Instream (Environmental) Flows⁶

Historically, water resources were managed to fulfill the needs of out-of-stream development, such as crop irrigation and municipal or industrial expansion. Water not withdrawn from a stream for economic development was generally considered wasted water. Water-flow needs for fish and wildlife

⁵Under the U.S. Department of the Interior’s Indian Water Rights Settlement Program, the Federal Government has refocused settlement of tribal water-right claims, shifting from litigation to negotiated settlements (U.S. BoR, 2012). Recent congressional hearings on “Indian Water Rights: Promoting the Negotiation and Implementation of Water Settlements in Indian Country” indicate that in the last dozen years, 27 tribal settlements were concluded based on this process, compared with less than 10 through the litigation process (U.S. Senate Committee on Indian Affairs, 2012). These settlements often involve, via congressional approval, allowing Tribes to assign, exchange, and lease their water rights to non-Indian users both on and off the reservation. While many Tribal water rights remain unquantified, these settlements enhance certainty in water-rights allocations and also may contribute to new investment in improved (more efficient) irrigation systems.

⁶Flow is generally measured as the volume of water per unit of time, usually cubic feet per second, and represents the amount of water flowing past a point in the river at a given time.

habitat and other ecosystem benefits were not a legally recognized water management priority. From the 1970s on, however, changing social values with respect to water quality and environmental/ecosystem services have had greater influence on Federal and State water-resource management institutions and policies. Changing environmental values initially led to the establishment of minimum streamflow requirements to meet legally recognized instream water needs. Subsequently, watershed/basin-level water management agencies were legally bound to manage water resources consistent with maintaining sustainable ecosystems.

Minimum streamflow management focused primarily on the need for a minimum amount of water to be left in a stream, generally to maintain fish habitat (Poff et al., 2003; Zellmer, 2009; MacDonnell, 2009). In basins with significant irrigation withdrawals, minimum flow provisions often reallocate water supplies from agriculture, particularly during low-flow (drought) years. More recently, the use of flow provisions designed to enhance ecosystem services has become broader in scope. Often referred to as “environmental flows,” these flow regimes are intended to provide multiple instream benefits, including enhanced filtration, dilution of sewage and other effluents, fish and wildlife habitat, recreation (fishing, hunting, boating, and environmental aesthetics), hydropower, navigation, groundwater recharge,⁷ riparian wetlands, and migratory bird habitat, as well as exotic species control and local/regional economic development (Sophocleous, 2007; Zellmer, 2008; MacDonnell, 2009).

Environmental flows will likely play an increasingly important role in the ongoing struggle among competing water demands. Most Western States have adopted some form of legislation establishing minimum instream flows, and provisions have evolved over time to reflect the complexities of hydrology and a range of instream uses.⁸ See the box, “Environmental Flows and Increasing Demand Pressures,” for examples of the growing pressure that environmental flows place on limited water supplies.

Water for Energy Expansion

U.S. energy sector growth, for production of biofuels and other energy sources, is expected to place increasing demand on water resources. In the Western States, where surface-water systems are already over-appropriated and groundwater aquifer levels are generally declining, energy-related water demand could directly affect irrigated agriculture.

An expanding biofuel sector will require water for both processing and feed-stock production. Water demand for a biofuel plant with a given processing capacity is generally known (an engineering relationship), local (site-specific), and typically managed through market-based permanent lease or purchase agreements between local farms and the biofuel firm. While total withdrawals for biofuel processing are comparatively low, local/regional impacts on water resources can be sizable. Water demands for irrigated feed-stock production for biofuel production, however, may be more significant. While some of this water demand will likely come from existing irrigated production, a growing biofuel industry may increase demand for irrigation water as producers respond to higher corn and soybean prices by expanding

⁷A system of using the hydrologic process to refill a groundwater aquifer by either pumping water back into wells or managing surface water to increase downward water percolation to the groundwater aquifer.

⁸The evolution and status of State-specific minimum instream-environmental flow programs, statutes, and policies, which vary widely across the Western States, have been summarized by MacDonnell (2009).

Environmental Flows and Increasing Demand Pressures

Changing societal values have focused greater attention on water resources to meet the needs for water quality, fish and wildlife habitat, and other ecosystem services. These water demands have often exceeded the historical “minimum instream-flow” requirement. The following examples demonstrate how providing water for “environmental flows” places increasing pressures on limited water supplies.

Stream and river restoration projects have become an important component of Federal and State environmental management programs. A recent study, based on a review of 37,099 projects in the National River Restoration Science Synthesis database, reported that the number of restoration projects has increased exponentially since 1990 (Sophocleous, 2007; Bernhardt et al., 2005). These restoration projects may be designed to achieve multiple objectives, including enhanced water quality; management of riparian zones; improved instream habitat for fish and other aquatic species; improved fish passage; bank stabilization; flood plain management; river/stream channel reconfiguration; and flow modification for fish, aesthetics, and recreation. The study estimated that from 1990 to 2004, more than \$14 billion was spent on stream/river restoration projects within the continental United States, averaging slightly more than \$1 billion annually.

In many Western States, water markets are increasingly being used to reallocate water from existing uses, particularly from agriculture, to enhance supplies for environmental flows within fully or over-appropriated basins. Many State water laws now recognize environmental flows as a beneficial use and allow State and nongovernmental organizations (NGOs), including conservation and environmental groups, to lease, purchase, or donate water or water rights to enhance river flows (Sophocleous, 2007; MacDonnell, 2009). Landry (1998) reported that from 1990 to 1997 about 2.4 million acre-feet (maf) of water was “leased, purchased, or donated for purposes of enhancing river flows in the Western United States.” While this does not reflect the total volume of water for instream flows (a quantity difficult to measure), by comparison, water transferred for environmental purposes represented about 5.2 percent of the quantity of surface water applied by irrigated agriculture in 1998.

From 2000 to 2005, the Colorado River Basin experienced the worst drought conditions in approximately 100 years, with Lake Powell and Lake Mead dropping to about 46 percent of combined water storage capacity (Jerla and Prairie, 2009). As a result, the Bureau of Reclamation (Reclamation), through the National Environmental Policy Act process, developed a management plan for the basin that included interim guidelines for coordinated water storage operations during Lower Colorado River Basin water shortages (U.S. BoR, 2007; Jerla and Prairie, 2009). The preferred management alternative for the basin included a “Conservation Before Shortage” alternative (developed by a consortium of eight environmental NGOs) to allow Reclamation to develop and manage voluntary compensated, conservation reduction/water-banking programs that would include water for environmental uses. In July 2006, these environmental NGOs submitted a new proposal, “Conservation Before Shortage II,” encouraging Reclamation to expand its use of voluntary market-based conservation mechanisms to provide water to protect but also enhance flow-dependent environmental values within the lower basin (Gillon et al., 2006).

--continued

Environmental Flows and Increasing Demand Pressures (continued)

Over the years, managing water supplies to enhance benefits for fisheries and ecosystem values has become an increasingly important focus for the Central Valley of California. The Central Valley Project (CVP), initially authorized in 1933 and completed in the early 1970s, is comprised of 18 dams and reservoirs and over 500 miles of canals and aqueducts. The project conveys about 7.4 maf of water annually from the Sacramento, Trinity, American, Stanislaus, and San Joaquin Rivers to agricultural users (irrigating more than 3.0 million acres), municipal users, and wildlife refuges and for recovery of endangered fish species in the Sacramento and San Joaquin Valleys and the San Francisco Bay/Delta Estuary. In 1992, the U.S. Congress adopted the Central Valley Project Improvement Act (CVPIA), which formally identified fish and wildlife protection, restoration, and mitigation as project objectives of equal priority with irrigation and other domestic uses, as well as required the CVP to contribute to the State's efforts to protect the Bay/Delta Estuary (U.S. BoR, 2009). The act also reallocated 800,000 acre-feet of water from existing users to fish and wildlife annually.

Since 1992, and after nearly \$1 billion had been spent on numerous restoration projects throughout the Central Valley, the CVPIA Program Activity Review (conducted by the U.S. Bureau of Reclamation) reported that "there is no basis to conclude" that the provisions of the CVPIA "have been satisfied" (U.S. BoR, 2009), while an independent review panel concluded that anadromous fish species had "stayed relatively even or declined from 1992-2005" (Circlepoint, 2008). Therefore, reallocating water supplies to meet environmental/ecosystem concerns within the Central Valley remains a high priority of the State/Federal partnership (CALFED), an agreement by 25 State and Federal agencies established in 2000 to "work collaboratively toward achieving balanced improvements" for the Bay/Delta Estuary (CALFED Bay-Delta Program, 2010).

More recently, efforts of the State and CALFED have taken on a larger ecosystem sustainability focus. In 2006, California State agencies initiated the Bay Delta Conservation Plan, a collaborative effort by State, Federal, and local water agencies; State and Federal fish agencies; environmental organizations; and other interested parties to identify water flow and habitat restoration actions designed to recover endangered sensitive species and their habitats in the Bay-Delta area, while also providing for improved reliability of water supplies (U.S. BoR, 2010). Draft habitat conservation plans for the Bay-Delta area are expected to be completed in 2012. Meanwhile, due to low reservoir storage associated with below-normal precipitation levels and the need to reallocate water supplies to protect native fish species, the California Department of Water Resources reduced 2010 water deliveries (from Northern California) to users in the Bay-Delta and Southern California (including agriculture) by some 800,000 acre-feet, or roughly half of normal allocations. In 2009, due to similar conditions, Southern California municipal and agricultural users of State Water Project water received only 40 percent of their normal allocations. Over the past 10 years, low reservoir storage and environmental flow demands across the Sacramento/San Joaquin Delta have limited water-supply deliveries to only 68 percent of normal allocations from the State Water Project, impacting water for over 25 million Californians and approximately 750,000 acres of irrigated farmland (DWR, 2010a and 2010b).

irrigated acreage for these crops. Chiu et al. (2009), in estimating the “embodied water in ethanol” (i.e., ethanol’s lifecycle water use), revealed that:

1. More corn production for ethanol was taking place within highly irrigated regions, particularly in the northern High Plains (Ogallala Aquifer) region;
2. Consumptive water use for bio-ethanol production in the United States increased 246 percent, from 1.54 to 4.95 maf, between 2005 and 2008; and
3. Total consumptive water use for bio-ethanol production (including water for irrigation) in the Ogallala Aquifer region increased from 1.95 maf in 2007 to 3.65 maf in 2008 (about 68 percent was supplied from groundwater).⁹

The National Research Council (2008) estimated that:

1. Irrigated corn for ethanol (in Nebraska) required about 780 gallons of freshwater withdrawals per gallon of ethanol; and
2. “While irrigation of native grass today would be unusual, this could easily change as cellulosic biofuel production gets underway.”

The U.S. Government Accountability Office (GAO) estimated the average water consumed in corn ethanol production (adjusting for irrigation return flows) for the Northern Plains States at 323.6 gallons of water per gallon of ethanol (U.S. GAO, 2009). Nearly 88 percent of this requirement is expected to come from groundwater.

The full impact of biofuel expansion on agricultural land and water resources, however, is expected to be complex, involving the substitution of land and water among crops, cropland expansion, reduced use of idled cropland, expanded use of applied inputs, and increased double-cropping (producing two crops on the same land within the same year), depending on where biofuel development occurs. Wallander et al. (2011) estimate that, since 2006, corn production expansion to meet biofuel feedstock demand came primarily from acreage shifts from soybean farms (53 percent), conversion of uncultivated hay and grazing land, and acreage formerly enrolled under the USDA Conservation Reserve Program (CRP) (33 percent). Increases in corn yields and double-cropping, and decreases in idled cropland, accounted for the remainder.¹⁰ Production response has varied across regions; shifts in crop acreage from soybean to corn acres have been the dominant production response in the Corn Belt and Lake States regions, while expansion in harvested cropland from new cultivated land has dominated the Northern and Southern Plains and the lower Mississippi River Valley.

Malcolm et al. (2009) drew similar conclusions regarding the impact of biofuel-sector growth on agricultural land-use decisions. Their estimates suggest that the substitution of soybean acres for corn acres would dominate cropland reallocation decisions across the Corn Belt, while expansion in harvested corn acreage (primarily from expired CRP contracts, pastureland, and idled cropland) explained a predicted increase in corn production in the Northern Plains. Based on a qualitative assessment, this research suggests that the expansion of corn acreage to meet biofuel feedstock demand has the

⁹Consumptive water-use estimates by Chiu et al. (2009) were in trillions of liters but are converted here (for consistency) to acre-feet units based on 3.7854 liters = 1 gallon and 325,851 gallons = 1 acre-foot.

¹⁰Acreage shifts from soybean farms could have included acres from other crops besides soybeans. In addition, Wallander et al. (2011) did not evaluate irrigated crop and water-use effects.

“potential for increased reliance on irrigation,” particularly for the Plains States. This would likely involve an increase in consumptive water use, both due to expanded irrigated corn acres and because water consumption by corn plants is greater than that for soybeans, placing additional pressure on groundwater resources where withdrawals have generally exceeded natural recharge. Increases in water demand for energy feedstock production could affect the long-term sustainability of surface and groundwater resources where they are currently under stress.

Water demands are also expected to increase due to growth and technical innovation forecast in other energy-related uses, including thermoelectric generating capacity, expected development of utility-scale solar power across the Southwestern United States, and potential development of a commercial oil shale industry in the Upper Colorado River Basin. In addition, expansion of hydraulic fracturing (fracking) for deep shale natural gas exploration is expected to increase energy sector water demand in the Eastern and Central United States. Hydraulic fracturing involves pumping water, sand, and chemicals under high pressure into a shale formation to generate fractures or cracks that allow natural gas to flow out of the rock and into the well. Water demand for hydraulic fracturing does not represent a long-term water resource commitment, as it occurs only during the drilling and completion phases of each well (Chesapeake Energy, 2011). However, the practice has raised public concern for groundwater quality.

Increased use of evaporative cooling technology for thermoelectric and solar power may significantly increase consumptive water-use requirements for the energy sector in areas where expansion occurs. Water demand for the oil shale industry could also be significant; ongoing studies by the U.S. Department of the Interior address the uncertainties of water resource impacts for this sector. For most new energy development, however, water quality and environmental impacts are potentially the more significant policy concern. Summarizing these water demands is outside the scope of this report due to the unique needs by energy type, the complexities of energy forecasts, technological uncertainties, and the lack of aggregate water-use estimates for projected energy expansion.¹¹

Climate Change and Water Resources

Substantial evidence demonstrates that the global climate is changing, with important implications for agriculture and water resources (IPCC Report, 2007; U.S. CCSP, 2008). In much of the Western United States, annual precipitation is projected to decline, particularly in the warmer summer months. Moreover, gradual temperature increases will shift the West’s traditional source of freshwater supplies from winter snowpack to more frequent and intense early spring rain (IPCC Report, 2007; Knowles et al., 2006). These shifts are expected to alter both the quantity and timing of associated streamflow, with more flow in the early spring, and to reduce late-season reservoir storage amounts from precipitation and late-spring and summer snowmelt. These streamflow and reservoir storage effects are expected to reduce water supplies for traditional peak irrigation water demands during the summer and fall growing seasons.

¹¹For more specific information on these water-use demands, see NETL, 2008; GWPC and All Consulting, 2009; U.S. DOE, 2010; U.S. GAO, 2010; Bartis et al., 2005; U.S. BLM, 2011.

Studies conducted for the Intergovernmental Panel on Climate Change's (IPCC) *Fourth Assessment Report* (IPCC Report, 2007) revealed that:

1. The April 1 snow-water equivalent snow cover "has declined 15 to 30 percent since 1950 in the western mountains of North America" (Mote et al., 2003 and 2005; Lemke et al., 2007); and
2. Streamflow over the last century has "decreased by about 2 percent per decade" in the Central Rocky Mountain region (Rood et al., 2005).

These studies indicated that these patterns were not uniform across the Mountain region and that, while there has been a general downward trend in snow-water equivalent snow across the Western States, decreases have been relatively larger at lower elevations. In addition, results from various climate simulation models or analyses based on multi-century tree-ring reconstruction (1490-1998) indicate that expected warming temperatures and precipitation changes will reduce streamflow in the Upper Colorado River Basin (UCRB). Streamflow could decline by 8-11 percent by the end of the 21st century, with declines as high as 25 percent by 2030 and 45 percent by 2060 (Christensen and Lettenmaier, 2007; Hoerling and Eischeid, 2007; McCabe and Wolock, 2007).¹²

Van Kirk and Naman (2008) estimated that 39 percent of the observed decline in the July-October discharge for the Scott River within the Klamath Basin could be explained by regional-scale climatic factors. The U.S. Climate Change Science Program's *Final Report of Synthesis and Assessment Product 4.3* (U.S. CCSP, 2008), drawing on 2007 IPCC climate change assessments and other studies, revealed significant regional differences in projected streamflow effects across the United States. The 2008 CCSP report projected that annual runoff would increase across the Eastern United States, gradually transition to little change in the Missouri and Lower Mississippi basins, and substantially decrease (by up to 20 percent) in the western interior (particularly the Colorado and Great Basin areas). Runoff projections for the West Coast (Pacific Northwest and California) were also negative, but smaller than in the western interior basins. The recent Bureau of Reclamation report to Congress (Reclamation, 2011) further disaggregated climatic impact and hydrologic projections to eight reclamation river basins. This study indicates that for the Colorado Basin, southern sub-basins are expected to experience greater warming and a decrease in precipitation; portions of the upper basin are expected to experience wetter conditions, but warming temperatures will dominate expected basin-wide effects. As a result, projected reductions in natural runoff and changes in runoff seasonality in the Colorado Basin are expected to reduce water supplies given current reservoir system capacity and operational regimes, with differences between northern and southern sub-basins. In addition, because reservoir storage opportunities are limited by flood control considerations, increased winter runoff is not expected to translate into increased water storage for the spring season. Reductions in runoff during the spring and early summer are expected to reduce reservoir levels and water supply deliveries during the irrigation season.

The 2011 Reclamation report indicates that warming temperatures are expected to be relatively uniform over the Columbia River Basin, with generally wetter conditions varying across sub-basins. Decreases in snowpack are expected to be more substantial over the western mountain ranges of the

¹²For information and maps of the major U.S. aquifer and river systems, see the U.S. Geological Survey (USGS) report for the *Groundwater Atlas of the United States* (USGS, 2011), which describes the location, extent, and the geologic and hydrologic characteristics of the major aquifers of the Nation, and the USGS Water Supply Paper 2294, *Hydrologic Unit Maps* (Seaber et al., 1987), which provides descriptions, names, and drainage areas of the major U.S. river basin hydrologic units.

basin and the lower elevations of the basin's eastern mountain ranges, which "contribute significantly to runoff in headwater reaches of major Columbia River tributaries." Snowpack in northern and higher elevations of eastern portions of the basin, however, are projected to increase overall. These impacts are expected to result in varied annual runoff across sub-basins, with changes in the southern and central portions of the basin expected to be less than in the northern sub-basins. In addition, the seasonality of runoff becomes more important as warming temperatures in the northern sub-basins cause more of the runoff to occur during the December-March (cool) season and decrease runoff during the April-July (warmer) season. The southern and central sub-basins (e.g., the Snake and Yakima Rivers) are expected to see little change in April-July runoff as increased precipitation could offset the cool-season warming effect. The Reclamation report (2011) recognized that, for the Columbia Basin, the impact on water supply and reservoir operations is less obvious because of the anticipated variability in climatic effects across sub-basins. The report also recognizes that, based on some studies, the general warming effects across the basin appear to have the most influence on runoff and ultimately on basin water supplies.¹³

Other climate change studies indicate that, as increasing temperatures thin snowpack and raise snowline elevations, mountain recharge rates will decline as recharge areas shrink, thereby reducing aquifer recharge and water-table levels (Dettinger and Earman, 2007; Hall et al., 2008). For the Ogallala Aquifer region, groundwater recharge is expected to decrease by more than 20 percent if temperatures increase by 4.5° F (2.4° C) (IPCC Report, 2007). Aquifer recharge rates could decrease by as much as 25 percent in the Ellensburg Basin of the Columbia Basin Plateau (NWAG Report, 2000). While these studies provide some initial information on how climate change may affect groundwater resources, these effects are not completely understood (USGS, 2009; Green et al., 2007). This uncertainty affects researchers' ability to isolate climate change influences on the subsurface hydrologic cycle and their effect on such factors as recharge, discharge, and groundwater storage. These factors are influenced significantly by groundwater-residence time—the time it takes climate variability and longrun climate change to affect a groundwater resource—which can range from days to tens of thousands of years. The longer the groundwater-residence time, the greater the challenge in detecting responses in groundwater supply due to climate variability and change.

Climate-induced declines in snowpack and altered runoff also create uncertainties involving the interactions between evapotranspiration (ET), mountain recharge versus alluvial (fan) basin recharge, and their combined effect on lower basin groundwater recharge (Dettinger and Earman, 2007). In addition, most groundwater systems have been altered substantially by human activities (Green et al., 2007). The USGS reports that improved groundwater-monitoring systems and an expanded research focus beyond groundwater-level fluctuations to address groundwater uncertainties and processes occurring over multiple decades will enhance our understanding of groundwater response to climate change (USGS, 2009).¹⁴

Moderate temperature increases are also expected to increase crop ET for the southern-tier Western States, increasing irrigation water demands in the region, while enhancing ET efficiency for many crops in the northern-tier

¹³Summarizing results here for the Colorado and Columbia River Basins was intended to illustrate the variability in climate change impacts on surface water supply, both across and within basins. For more information on how projected climate change affects water supplies for other river basins, see the Reclamation report (U.S. BoR, 2011) at <http://www.usbr.gov/climate/SECURE/docs/SECUREWaterReport.pdf>.

¹⁴The USGS and the U.S. Department of Agriculture (USDA), in conjunction with the United Nations project Groundwater Resources Assessment under the Pressures of Humanity and Climate Change (GRAPHIC), are assessing climate change effects on the High Plains Ogallala Aquifer (USGS, 2009).

Western States.¹⁵ Even for northern-tier States, however, moderate warming conditions will likely still impact irrigation water demands because, with less total water supply, the timing of irrigation becomes a more critical onfarm water management issue. In the Eastern United States, where precipitation is generally sufficient to support rainfed crop production, climate-induced changes in irrigation to meet water demands will depend on shifts in normal growing-season rainfall, potential increases in the frequency and severity of drought, and relative returns to irrigated and dryland production.

The Challenge for Agricultural Water Conservation

New pressures on regional water budgets, particularly in the Western States, have raised important questions concerning the sustainability of water resources for irrigated agriculture:

1. Can irrigated agriculture adapt to climate-adjusted water supplies and emerging water demands through conventional means alone (i.e., the adoption of more efficient irrigation technologies, improved water management practices, and/or cropland allocation shifts)?
2. What changes in water institutions may be needed to complement and drive water conservation policy to more effectively manage increasingly scarce water supplies for agriculture?
3. How will these changes impact irrigated agriculture, land and water resource use, the environment, and rural economies?

Sustainability of U.S. Western Irrigated Agriculture

The critical link between climate change vulnerability and sustainability is *adaptability* (Wall and Smit, 2005; Hall et al., 2008; IPCC Report, 2007; Brekke et al., 2009).¹⁶ Reduced water supplies due to climate change will likely further constrain already over-allocated water resources across much of the Western United States, while increased water demand from alternative user groups, ecological requirements, and Native American claims will put additional pressure on water allocations. For agriculture, increased competition underscores the importance of managing irrigation applications (i.e., being capable of applying water at the time and in the amount needed to meet consumptive use requirements by crop growth stage). In addition, high-pressure sprinkler and traditional gravity irrigation systems will become even less efficient as application losses increase due to higher evaporation rates caused by rising temperatures.

Given current and projected climate changes, the adaptability of western irrigated agriculture to a more sustainable future could involve more widespread use of efficient gravity and pressurized irrigation systems, coupled with intensive field-level water management practices to enhance irrigation efficiency and potential farm water savings. Such practices may include the use of soil- or plant-moisture-sensing devices, commercial irrigation-scheduling services, and computer-based crop-growth simulation models that help producers decide when and how much to irrigate.

Practices that enhance gravity-flow systems through improved distributional uniformity of field-water advance include field laser leveling, gated pipe

¹⁵Crop evapotranspiration (ET) is generally defined as the loss of water to the atmosphere through evaporation (from soil and plant leaf surfaces) and transpiration (water from inside the plant that vaporizes through plant stomata or microscopic pores on plant leaf surfaces). Crop ET-efficiency, as used here, refers to the effect that rising temperatures have on crop yield per unit of water consumed in ET, alternatively recognized as crop water-use efficiency (Izaurre et al., 2003; Hatfield et al., 2008; Bates et al., 2008). Rising temperatures are expected to reduce crop yield per unit of ET in the southern-tier Western States, while having a positive effect in the northern-tier Western States.

¹⁶The terms “water conservation,” “sustainable water use,” and “adaptation” have been widely used in economic literature, but consistent definitions are somewhat elusive. For the purposes of this report, we define sustainable irrigation water use as a goal of conservation policy—ensuring a viable irrigated agriculture sector and adequate agricultural water availability for future generations, while also protecting offsite environmental services. This definition is consistent with most USDA reports that address sustainable agriculture. Adaptation strategies involve various mechanisms for achieving agricultural water conservation and allocation goals.

systems with surge flow/cablegation, shortened furrow lengths, alternate-row irrigations, reduced irrigation set times, and polyacrylamide (PAM) applications (a water-soluble soil amendment that stabilizes soil and waterborne sediment). Tailwater pits may also be used to capture and reuse irrigation drainage from the field. Pressurized system enhancements, including low-energy precision application/drop-tube systems, micro-irrigation systems, and automated nozzle control systems, improve the precision of applied water while reducing energy requirements for pressurization.

Under the more efficient gravity and pressurized irrigation systems, intensive infield water management practices can enhance a producer's ability to apply water closer to a crop's consumptive use requirement. This is especially important when deficit irrigating a crop to maximize profits, particularly during drought years. Deficit irrigation is an applied water management strategy that concentrates the application of limited seasonal water supplies on moisture-sensitive crop growth stages to maximize the productivity of applied water. The quantity of water applied provides less than the full crop ET requirement, which inevitably results in plant moisture stress and reduced crop yield. With deficit irrigation, however, the farmer's goal is to maximize profits (net income) per unit of water used rather than per land unit used for production (Feres and Soriano, 2007; Geerts and Raes, 2009). Thus, appropriately integrating water management practices with efficient irrigation systems improves the adaptability of irrigated agriculture to water-supply deficits, while enhancing longrun sustainability.

Sustainability of U.S. Eastern Irrigated Agriculture

Conservation also ensures a more sustainable future for irrigated agriculture in the 31 Eastern States. In the more humid East, irrigation generally complements growing-season precipitation that normally provides sufficient water to meet crop consumptive use requirements in average rainfall years. When precipitation during the crop-growing season falls short, some producers supplement with irrigation to meet crop water-use requirements.¹⁷ Historically, irrigated production has accounted for a small share of crop production in the Eastern States. Since the mid-1990s, however, crop irrigation has expanded significantly across the East, increasing by nearly 20 percent from 1998 to 2008 and by 15 percent since 2003 (USDA/NASS, 2010).¹⁸ Irrigation has increased in the Eastern States primarily because of increases in commodity prices and yields, increased risk avoidance due to recurring drought conditions, and access to available groundwater supplies at relatively low cost due to shallow aquifer pumping depths (Midwest Irrigation, 2010; Fischer Farm Services, 2011; Evett et al., 2003; Vories and Evett, 2010).

In 2008, nearly 79 percent of crop water applied in the Eastern States was pumped from shallow aquifers subject to annual recharge that also often serve as the primary source for downstream surface-water flows for nonagricultural uses (USDA/NASS, 2010; USGS, 2011). Less than 4 percent of the water for eastern irrigated agriculture has come from off-farm water sources. At the same time, population growth has increased water demand to meet the needs of urban/industrial growth and recreation, while changing social values have increased pressure for improved water quality and ecosystem services. Water supplies also have tightened in many eastern watersheds. Expanded

¹⁷While all irrigation is supplemental to rainfed crop production, irrigation in humid regions is often referred to as supplemental (or complementary) within the scientific literature (Evans and Sadler, 2008; Clemmens et al., 2008) because irrigation in humid regions is understood to be a "tactical measure to complement reasonably sufficient rainfall and to stabilize production despite short-term droughts" (Evans and Sadler, 2008).

¹⁸The largest irrigation increases in the East since 1998 have been in the Southeast (Georgia at 56 percent and Alabama at 60 percent), the Lower Mississippi Delta (Missouri at 48 percent, Arkansas at 11 percent, and Mississippi at 31 percent), and the Upper Midwest (Minnesota at 57 percent and Michigan at 45 percent).

groundwater use for irrigated agriculture has contributed to declining aquifer water levels, rising pumping costs, and saltwater intrusion near coastal regions. The increasing importance of groundwater resources for nonagriculture uses, the lack of reliable surface-water supplies because of limited annual carryover storage capacity, rising irrigation pumping costs, and water-quality concerns from irrigation system losses have all heightened concerns for onfarm water conservation as a critical component of a sustainable irrigated agriculture sector in the Eastern States. As a result, advancing onfarm water conservation is as important throughout much of the 31 Eastern States as it is in the 17 Western States.

How Important Is Irrigation to U.S. Agriculture?

Nationwide, irrigated agriculture makes a significant contribution to the value of U.S. agricultural production. In 2007, the market value of all agricultural products sold was \$297.2 billion, with irrigated farms (farms with at least some irrigated cropland) accounting for roughly 40 percent of market sales, or \$118.5 billion, and nonirrigated farms (farms not irrigating any cropland) accounting for the remainder (table 1). While the average per-farm value of agricultural products sold by all farms in 2007 was \$143,835, the average value for irrigated farms was nearly 2.5 times higher, at \$344,413. The average value of farm products sold by irrigated farms was 3.3 times the average value for nonirrigated (dryland) farms.

Irrigation also contributes to the value of livestock and poultry products via irrigated crop production used as animal forage and feed. In 2007, the total value of crop products sold (including nursery and greenhouse crops) by irrigated farms was \$78.3 billion, representing 54.5 percent of the value of crop sales by all farms (table 1). For irrigated farms only, the value of crop products sold accounted for nearly 67.0 percent of their agricultural sales in 2007,

Table 1

Market value of agricultural products sold and farm production expenses for irrigated and nonirrigated farms, 2007

Farm characteristic	All farms	Irrigated farms		Dryland farms (farms with no irrigated cropland)
		All irrigated farms (mixed irrigated and dryland cropland)	Farms with all harvested irrigated cropland (no dryland cropland)	
Market value of agricultural products sold (\$1,000)	297,220,491	118,510,873	65,333,520	178,709,618
Average per farm (\$)	143,835	344,413	349,989	103,762
Crops, including nursery and greenhouse crops (\$1,000)	143,657,928	78,297,158	46,872,638	65,360,770
Average per farm (\$)	145,686	342,812	333,485	86,264
Livestock, poultry, and their products (\$1,000)	153,562,563	40,213,715	18,460,881	113,348,848
Average per farm (\$)	142,146	347,575	400,288	117,507
Total farm production expenses (\$1,000)	241,113,666	93,256,498	50,648,686	147,857,169
Average per farm (\$)	109,359	309,793	309,041	77,666
Energy-related expenses (excluding custom work) (\$1,000)	18,829,794	8,145,691	4,500,636	10,684,103
Average per farm (\$)	11,376	29,840	30,886	7,485

Source: USDA, National Agricultural Statistics Service, 2007 Census of Agriculture, 2009.

with livestock products accounting for roughly a third of market sales.¹⁹ In general, nonirrigated farms were more dependent upon livestock and poultry sales; crop sales accounted for 36.6 percent of agricultural product sales in 2007, while livestock/poultry sales accounted for 63.4 percent.

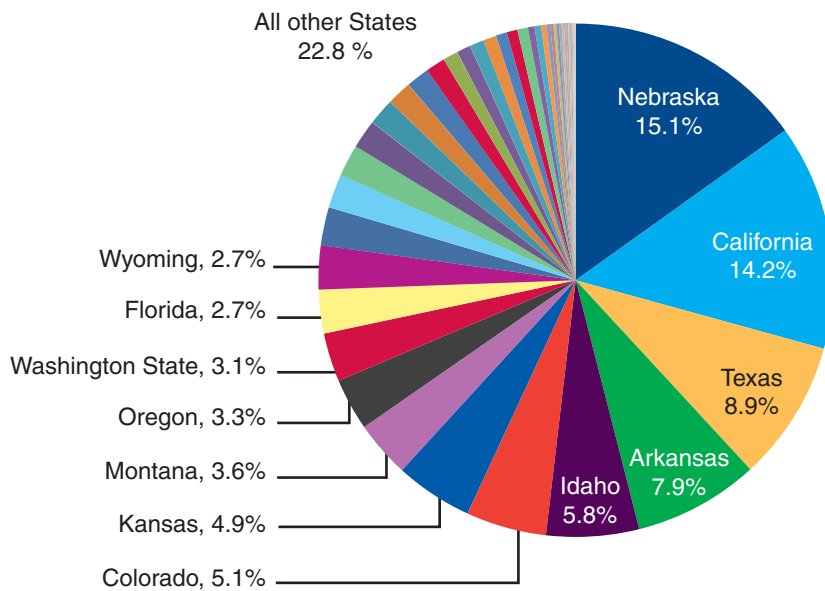
Where Does Irrigation Occur and What Does It Produce?

In 2007, 56.6 million farmland acres were irrigated across the United States (51.5 million acres of harvested cropland and 5.1 million acres of pastureland and other cropland), accounting for about 7.5 percent of all cropland and pastureland. About 16.6 percent of U.S. harvested cropland acres were irrigated, while only 1.2 percent of pastureland acres were irrigated (USDA/NASS, 2009). Nearly three-quarters of U.S. irrigated agriculture occurred in the 17 contiguous Western States, including 73.0 percent of harvested irrigated cropland and 94.0 percent of irrigated pastureland.

For 2007, 12 leading irrigation States accounted for 77.3 percent of all irrigated acres, including harvested cropland, pasture, and other lands (fig. 3). Nebraska's 8.6 million irrigated acres led all other States (15.1 percent of the U.S. total), followed by California with 8.0 million acres (14.2 percent), and Texas with 5.0 million acres (8.9 percent). Two Eastern States—Arkansas and Florida—were among the 12 leading irrigation States. Arkansas accounted for 4.5 million acres (7.9 percent) and Florida for 1.6 million acres (2.7 percent) of total U.S. irrigated acres.

¹⁹The relative importance of irrigated forage and feed production varies across States. In California, irrigated forage acres (mostly alfalfa and hay) account for nearly 90 percent of acres devoted to irrigated forage and corn for grain production. In the Plains States, however, irrigated corn for grain acres dominate production acres for irrigated forage and corn for grain, ranging from 67 percent in Texas to 85 and 92 percent in Kansas and Nebraska, respectively. We computed these statistics based on data from the 2007 Census of Agriculture (USDA/NASS, 2009).

Figure 3
State shares of total U.S. irrigated acres, 2007

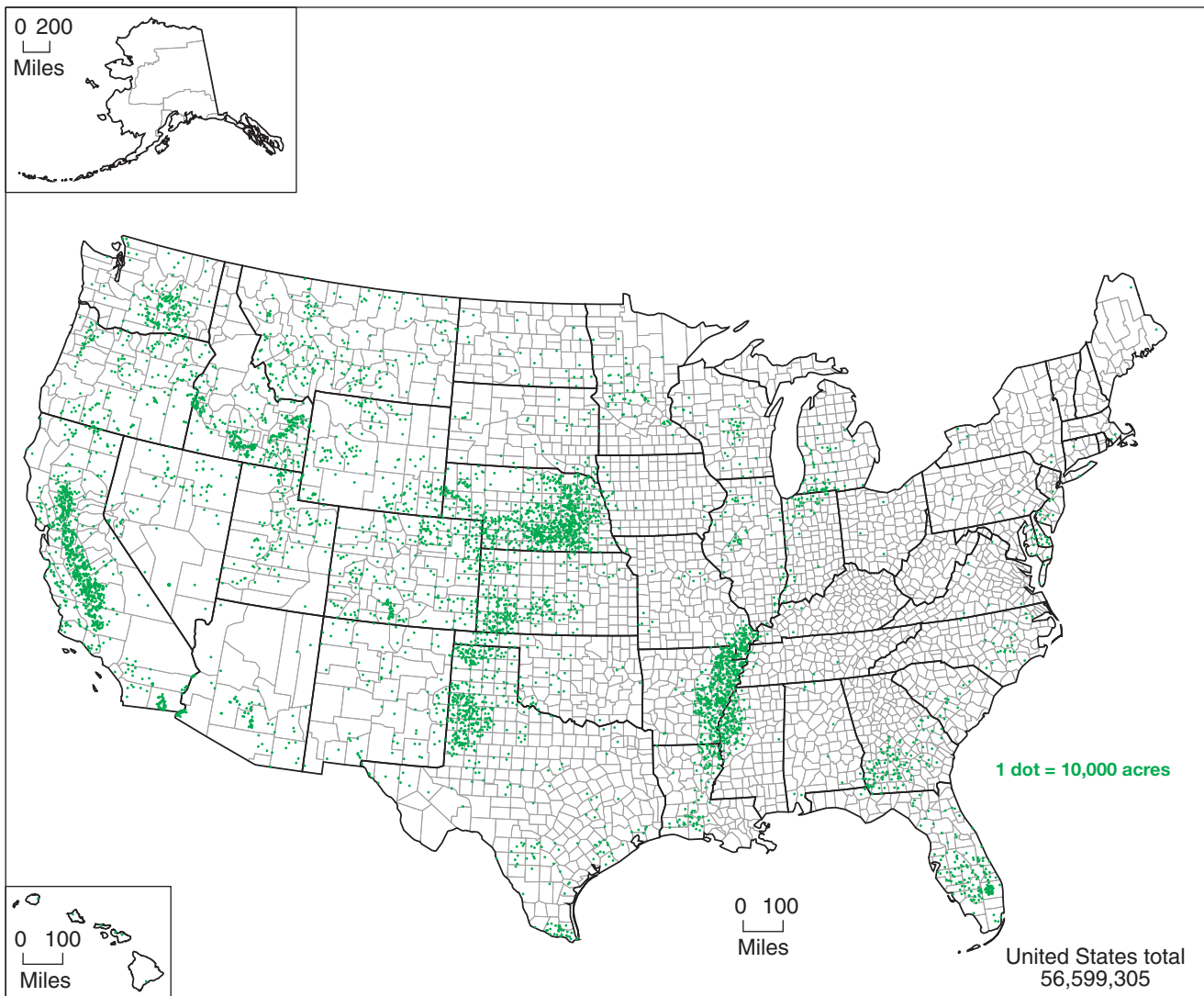


Note: Twelve leading irrigation States (10 from the West, and Arkansas and Florida from the East) accounted for 77.3 percent of U.S. irrigated acres, including harvested cropland, pasture, and other lands.
Source: USDA, National Agricultural Statistics Service, 2007 Census of Agriculture, State data, 2009.

Figure 4 illustrates the spatial distribution of irrigated acres in 2007, with each dot representing 10,000 acres (fig. 5 identifies States by USDA farm production region). Irrigated agriculture and water use are not static; some areas of use grow and some decline over time, influencing regional demands for water, energy, and other inputs. From 2002 to 2007, agricultural water use reflected a net increase of nearly 1.3 million irrigated acres across the United States. Nebraska accounted for nearly a million of those additional acres, with lesser increases in Arkansas, Colorado, Mississippi, Missouri, and Georgia. Irrigated acreage expansion in these States was attributed to availability of water supplies, improved irrigation economics (partly due to higher crop yields and reduced water costs associated with more efficient irrigation systems (USDA/NRCS, 2006)), increased biofuel demand for corn, recurring regional drought conditions, and the prospect of future restrictions on new irrigation development (at least for Nebraska).²⁰ California and Florida led

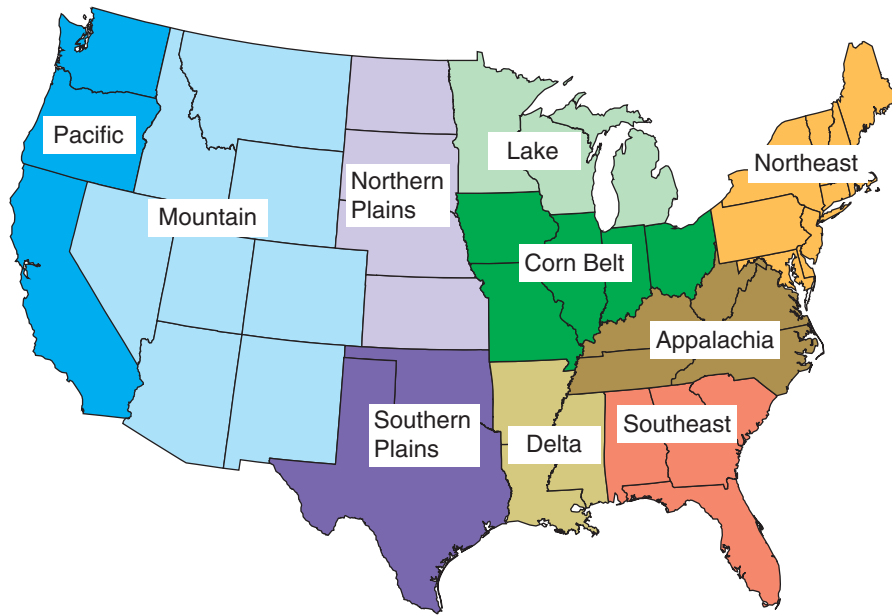
²⁰Personal communication with Raymond J. Supalla, University of Nebraska – Lincoln, Agricultural Economics Department.

Figure 4
Acres of irrigated land, 2007



Source: USDA, National Agricultural Statistics Service, map # 07-M080, www.agcensus.usda.gov/Publications/2007/Online_Highlights/Ag_Atlas_Maps/Farms/Land_in_Farms_and_Land_Use/07-M080-RGBDot1-largetext.pdf.

Figure 5
USDA farm production regions¹



¹The 17 Western States include those within the Northern Plains, Southern Plains, Mountain, and Pacific regions. The 31 Eastern States include those within the Lake, Corn Belt, Northeast, Appalachia, Delta, and Southeast regions.

among States where irrigated acres fell from 2002 to 2007, with declines of nearly 0.7 million acres and 0.3 million acres, respectively.^{21, 22}

Figures 6 and 7 illustrate the longer term changes that have taken place since the early 1980s in irrigated acres and agricultural water applied, respectively, by farm production region. From 1982 to 1997, irrigated acres increased for most farm regions. Since 1997, however, most regions saw either a decline in irrigated acres or a slowing of irrigated expansion. The largest growth in irrigated acres since 1997 was concentrated in the Northern Plains, Delta, and Corn Belt regions, with more moderate expansion across the Eastern United States (except Florida). Growth rates in the Northern Plains (primarily Nebraska) pushed irrigated acreage (at 11.9 million acres in 2007) above acreage irrigated in the Pacific region (at 11.6 million acres). Similarly, since 1997, irrigated acres in the Delta region surpassed acres irrigated in the Southern Plains. Over the same period, irrigated acres contracted in the relatively arid Mountain, Pacific, and Southern Plains regions.

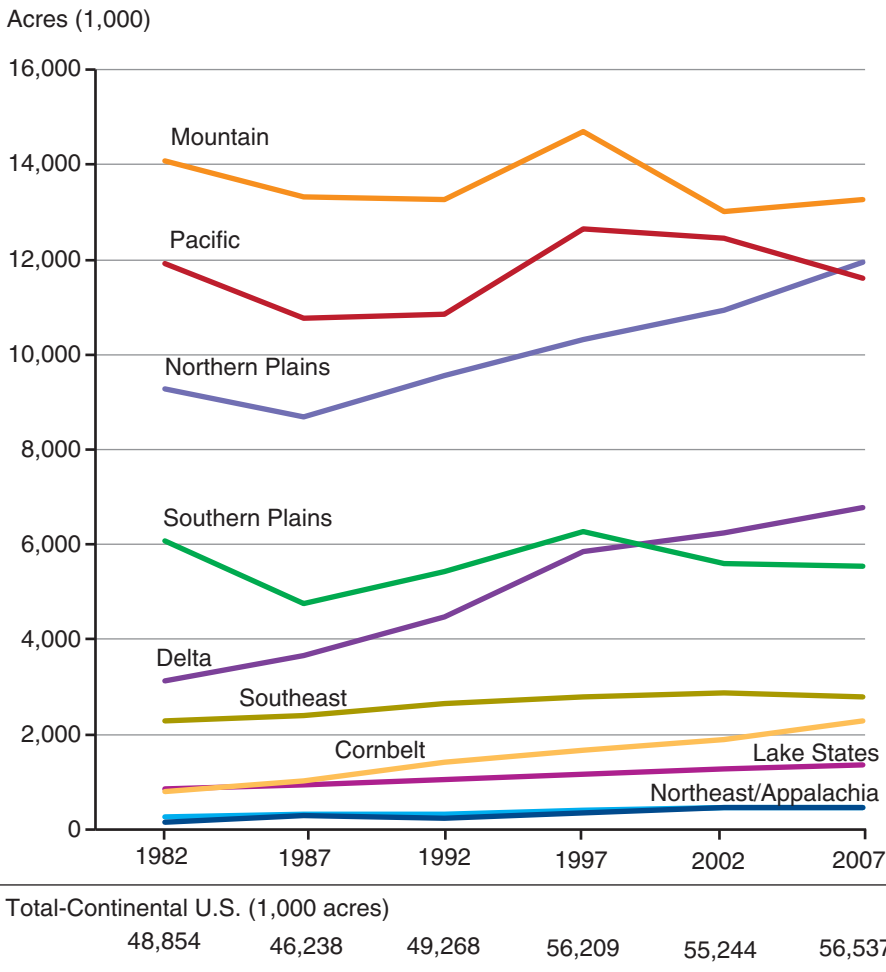
Agriculture in the Pacific region depended the most on irrigation, with more than half (53 percent) of cropland acreage irrigated in 2007. Other arid western regions with sizable concentrations of irrigated cropland include the Mountain (30 percent), Northern Plains (12 percent), and Southern Plains (12 percent) regions. In the Eastern States, irrigated acreage accounted for 36 and 22 percent of cropland in the warmer Delta and Southeast regions, respectively, but less than 4 percent of cropland acreage in the middle- and northern-tier regions.

Although more acres were irrigated in the Mountain States than in the Pacific or Northern Plains States, agriculture in the Pacific region uses significantly

²¹Florida's irrigated acres have been decreasing for a variety of reasons, including: (1) loss of irrigated acreages due to the reallocation of water supplies to restore the Florida Everglades ecosystem; (2) declining groundwater aquifer levels and saltwater intrusion; (3) loss of competitive markets; (4) urbanization; and (5) crop diseases (Aillery et al., 2001; USGS, 2008; Florida DEP, 2010).

²²In California, irrigated acres have been declining due to: (1) increased use of pumping restrictions on water supplies from the San Francisco Bay-Delta Estuary to meet environmental regulations imposed to protect endangered species; (2) continued urban growth (although more recently at a slower pace due to current economic conditions); and (3) reduced soil productivity due to increasing salinity (particularly in the Imperial and San Joaquin Valleys). Recurring droughts have heightened water-supply pressures in California, resulting in significantly increased Delta pumping restrictions and subsequent reductions in crop irrigated acres (Ayars, 2010; California Department of Conservation, 2011).

Figure 6
Irrigated acres by farm production region, 1982-2007



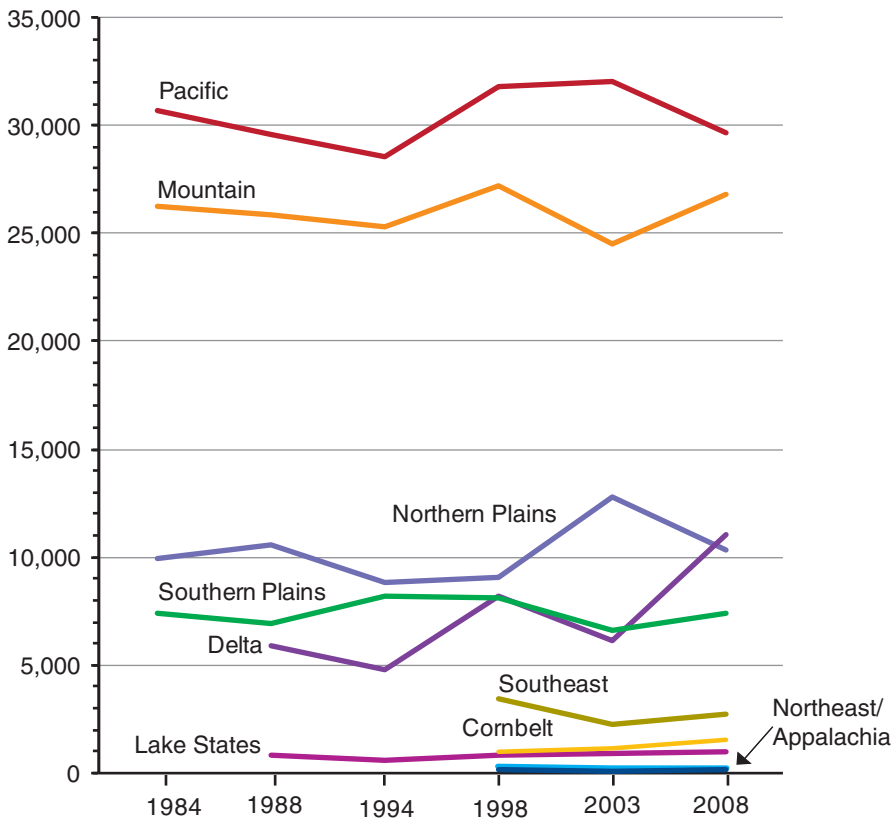
Source: USDA, Economic Research Service calculations based on data from USDA, National Agricultural Statistics Service, 1982-2007 Censuses of Agriculture.

more water overall due to higher application rates (fig. 7). Average per-acre field-level water use for agriculture in the Pacific region was 2.76 acre-feet, compared with 1.85 acre-feet in the Mountain States. Differences reflect regional variation in crop consumptive use requirements associated with climate and cropping pattern choices, as well as variation in the contribution of natural precipitation. Applied water rates are likely also influenced by differences in irrigation efficiencies, water prices, and energy costs for irrigation pumping. Irrigated agriculture within the Pacific and Mountain States accounted for the largest share (65.0 percent) of total agricultural water applied across the United States.

What does irrigated agriculture produce? Irrigated agriculture accounts for a share of harvested acreage for most U.S. crops. For example, vegetable, orchard, and rice crops had the dominant share of their harvested acres irrigated in 2007: 70 percent of vegetable acres, 79 percent of orchards, and 100 percent of rice (fig. 8). For all other crops, irrigated acreage accounted for less than half of U.S. harvested acreage by crop, with shares ranging from 39 percent for cotton to 5 percent for oats.

Figure 7
Agricultural water applied by farm production region, 1984-2008

Acre-feet (1,000) per year



Total-Continental U.S. (1,000 acre-feet)					
1984	1988	1994	1998	2003	2008
74,276	79,547	76,167	89,893	86,588	90,781

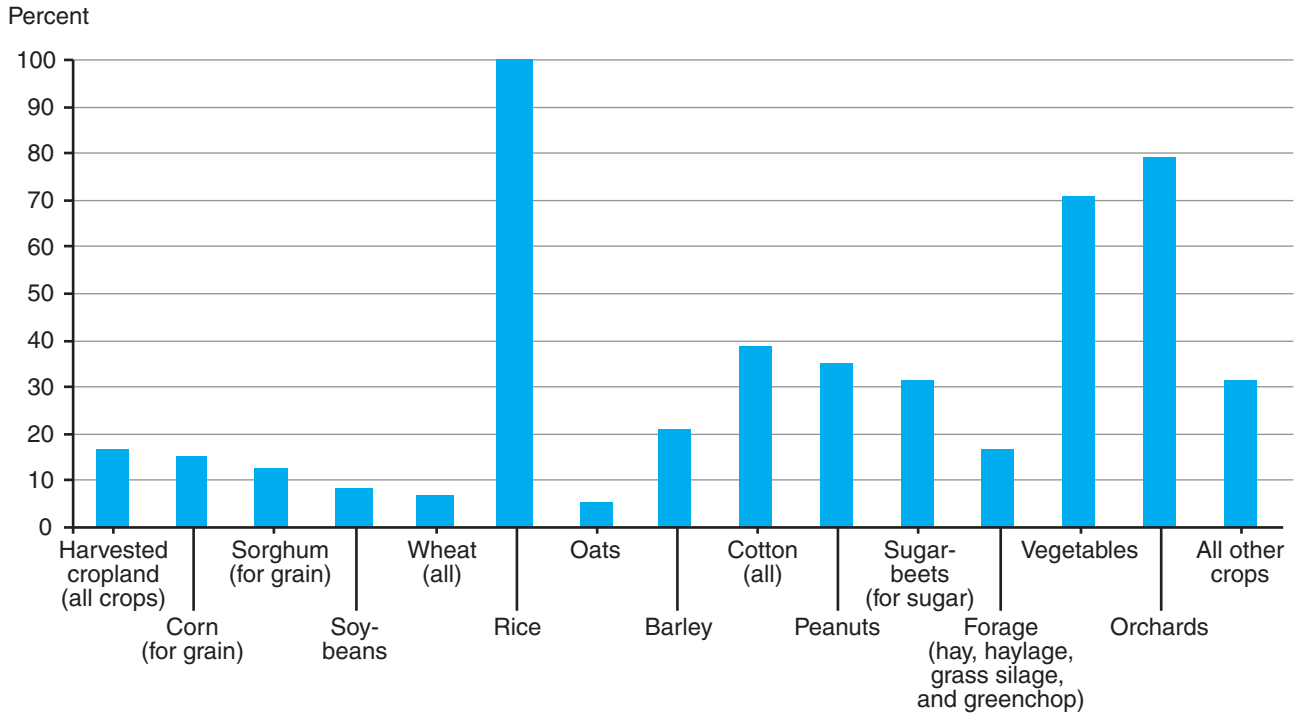
Source: USDA, Economic Research Service calculations based on data from USDA, National Agricultural Statistics Service, 1984-2008 Farm and Ranch Irrigation Surveys.

Irrigated cropping patterns differ regionally across the United States. For the West, the cliché that “if a crop is not irrigated, it is not grown” is not universally true. For rice, peanuts, vegetables, and orchard crops, more than 80 percent of each of their harvested cropland acres were irrigated in 2007 (fig. 9). Other crops grown in the West that relied heavily on irrigation included forage crops (31 percent of harvested acres), corn for grain (41 percent), cotton (43 percent), and sugarbeets (63 percent). As much as 75-95 percent of the harvested cropland acres for sorghum, soybeans, wheat, oats, and barley in the West were farmed using dryland production practices.

Figure 10 illustrates the relative distribution of 2007 harvested irrigated acres in the West by major crop category. Corn for grain and forage crops (hay, haylage, grass silage, and greenchop) accounted for about 52 percent of all harvested irrigated crop acres across the 17 Western States. Figure 11 shows the relative distribution of harvested irrigated acres for the 31 Eastern States in 2007. Corn for grain, soybeans, rice, and cotton accounted for 76 percent of all harvested irrigated crop acres in the East. Vegetables, along with orchards, vineyards, and nut trees, accounted for an additional 11 percent of

Figure 8

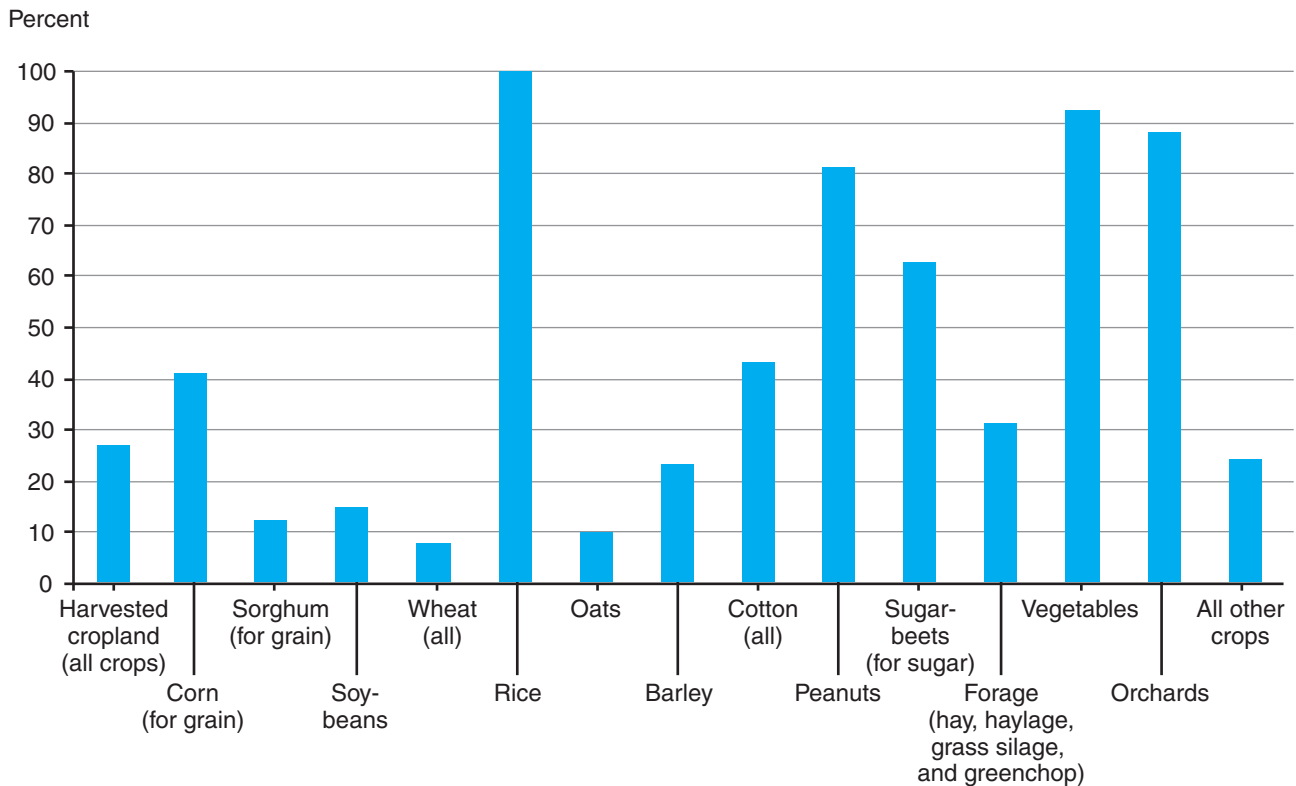
Share of U.S. total harvested cropland acres irrigated, all crops and by major crop category, 2007



Source: USDA, National Agricultural Statistics Service, 2007 Census of Agriculture.

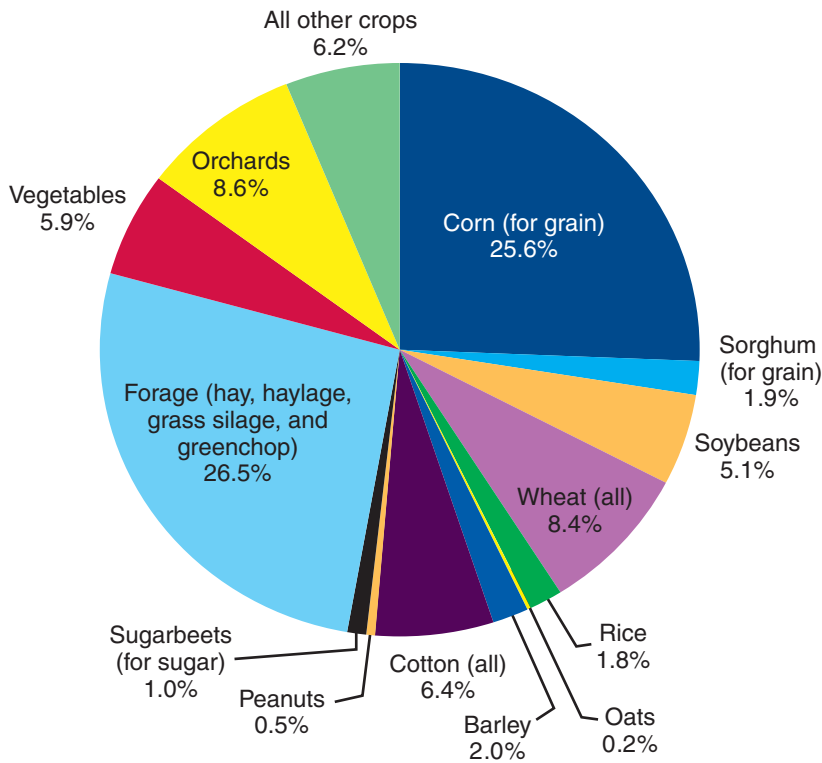
Figure 9

Share of total harvested cropland acres irrigated, by major crop category, for 17 Western States, 2007



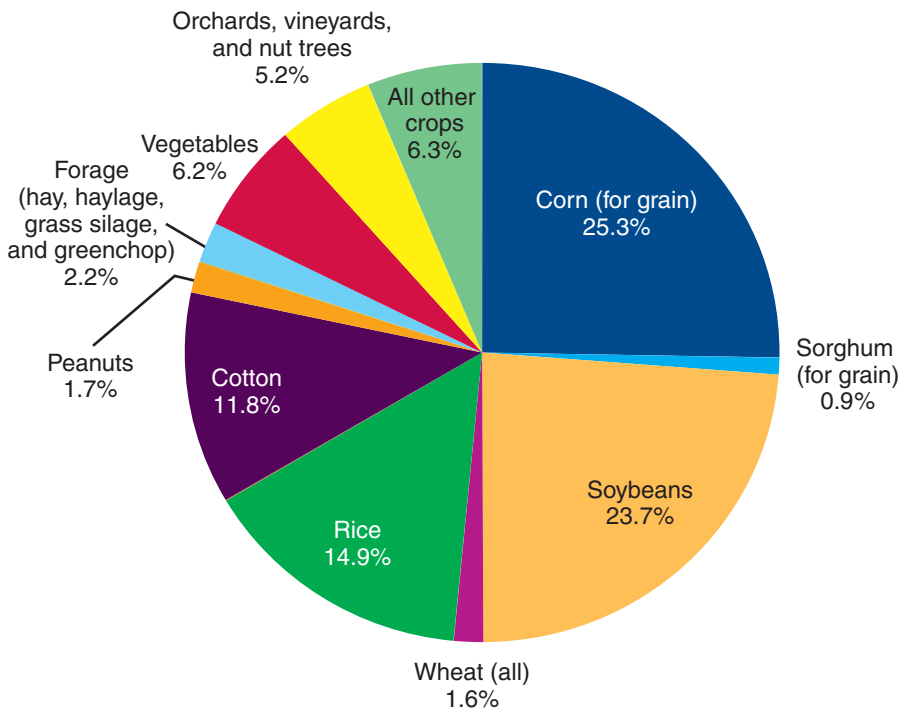
Source: USDA, National Agricultural Statistics Service, 2007 Census of Agriculture.

Figure 10
Distribution of harvested irrigated acres, by major crop category, for 17 Western States, 2007



Source: USDA, National Agricultural Statistics Service, 2007 Census of Agriculture.

Figure 11
Distribution of harvested irrigated acres, by major crop category, for 31 Eastern States, 2007



Source: USDA, National Agricultural Statistics Service, 2007 Census of Agriculture.

irrigated harvested acreage. Relative to the Western States, the irrigated cropping pattern in the Eastern States reflects a smaller share of irrigated acres for forage crops and wheat, and a larger share of irrigated acres devoted to rice and soybeans.

How Much Water Is Applied, What Is Its Source, and What Does It Cost?

In 2008, irrigators across the Western States applied nearly 74.2 maf of water for irrigated cropland production, averaging about 2.1 acre-feet per irrigated acre overall (table 2). Much of this water (52.4 percent) originated from surface-water sources, with the remainder (47.7 percent) supplied from wells used to pump groundwater from local and regional aquifers. Surface water originates from both onfarm and off-farm sources.²³ Onfarm surface water comes from onfarm ponds, lakes, or streams and rivers, accounting for roughly 15 percent of total agricultural water applied in the West, while off-farm water sources account for nearly 38 percent of total water applied. Water from off-farm sources is generally supplied to the farm through local irrigation districts; mutual, private, cooperative, or neighborhood water-delivery “ditch” companies; or from commercial or municipal water systems. Applied water from groundwater sources in the West averaged about 1.4 acre-feet per irrigated acre in 2008 (table 2). In contrast, applied water averaged 1.7 acre-feet per acre for onfarm surface water and 2.2 acre-feet per acre for off-farm surface water over the same period. These application differences likely reflect the generally higher cost of groundwater and the fact that more off-farm surface water is applied to higher valued, more water-intensive crops. In addition, more efficient systems are more likely to be used where

²³USDA’s 2008 Farm and Ranch Irrigation Survey (FRIS) is the most comprehensive source of nationally consistent information on irrigation water use and cost by water source (surface or groundwater). FRIS cost data include information on energy costs, irrigation repair and labor costs, and purchased water costs.

Table 2
Water application statistics for the 17 Western States, by type of irrigation and water source, 2008

	Total water applied (acre-feet)	Type of irrigation ¹					
		Gravity systems (acre-feet)	Percent gravity	Sprinkler/drip-trickle (pressure) systems (acre-feet)	Percent pressure	Other systems (sub-irrigation, miscellaneous, etc.) (acre-feet)	Percent other
Water applied	74,199,593	35,646,167	48.0	38,187,806	51.5	365,620	0.5
Average application (acre-feet/acre)	2.05	2.37		1.38			
		Water source ¹					
		Wells		Surface water sources			
		Groundwater (wells) (acre-feet)	Percent ground-water	Onfarm surface water (acre-feet)	Percent onfarm surface	Off-farm surface water (acre-feet)	Percent off-farm surface
Water applied	74,199,593	35,364,408	47.7	10,800,252	14.6	28,034,933	37.8
Average application (acre-feet/acre)	2.05	1.42		1.71		2.24	

¹USDA, Economic Research Service calculations based on data from the USDA, National Agricultural Statistics Service, 2008 Farm and Ranch Irrigation Survey.

Source: USDA, National Agricultural Statistics Service, 2008 Farm and Ranch Irrigation Survey, 2010.

groundwater is the primary water source. Center-pivot systems, for example, tend to be the more cost-effective system when drawing on groundwater. More than half (51.5 percent) of agricultural water for crop production in the Western States was applied using pressure-irrigation (sprinkler or drip-trickle) systems, with the remainder applied with gravity irrigation systems.²⁴ Application rates using gravity systems, which are generally less water-use efficient and more likely associated with lower cost surface water, averaged about 2.4 acre-feet per acre, while rates for sprinkler/drip-trickle systems averaged about 1.4 acre-feet per irrigated acre.

With irrigated production, water is pumped from groundwater wells, surface-water sources, or from water-delivery ditches (canals). Pumps are also used to pressurize field-level sprinkler or drip/trickle irrigation systems. As a result, producers typically incur significant expenses over and above normal crop production costs under nonirrigation production. Both capital (irrigation conveyance and distribution systems) and variable irrigation costs (depending on the quantity of water used) vary significantly by region and across irrigated crops. These cost differences impact irrigation profitability, which will fluctuate based on available water sources, type of irrigation system used, crops irrigated, energy source used to power irrigation pumps, and water costs charged for off-farm water supplies.

In 2008, irrigated agriculture in the Western States incurred over \$2.3 billion in energy expenses for onfarm pumping of irrigation water (table 3). Costs for pumping water from wells and for pressurizing irrigation systems averaged about \$76 per irrigated acre, compared with about \$38 per irrigated acre

²⁴For more information on gravity and pressure (sprinkler) irrigation systems, see *Irrigation Systems and Land Treatment Practices* at <http://www.ers.usda.gov/Briefing/WaterUse/glossary.htm>.

Table 3
Irrigation cost statistics for the 17 Western States, by type of irrigation expense, 2008¹

Energy expenses for onfarm pumping of irrigation water, by water source ²				Irrigation maintenance and repair expenses		
Total pumping expenditures		Expenses per irrigated acre		Total expenditures	Average cost per irrigated acre	
Water from wells	Surface water	Water from wells	Surface water			
<i>\$1,000 dollars</i>		<i>Dollars per acre</i>		<i>\$1,000 dollars</i>	<i>Dollars per acre</i>	
1,954,797	350,824	75.79	37.83	659,575	19.69	
Irrigation labor costs by type (hired and contract labor)				Purchased water costs for off-farm water supplies		
Total expenses		Average cost per irrigated acre		Total purchased water expenditures	Average cost	
Hired labor	Contract labor	Hired labor	Contract labor		Per acre	Per acre-foot
<i>\$1,000 dollars</i>		<i>Dollars per acre</i>		<i>\$1,000 dollars</i>	<i>Dollars per acre</i>	
748,620	121,384	33.26	20.16	671,491	66.28	23.95

¹USDA, Economic Research Service calculations based on USDA, National Agricultural Statistics Service, 2008 Farm and Ranch Irrigation Survey.

²Includes expenditures for all energy sources (electric, natural gas, LP gas, propane, butane, diesel fuel, gasoline and gasohol), except for solar.

Source: USDA, National Agricultural Statistics Service, 2008 Farm and Ranch Irrigation Survey, 2010.

for water supplied from a surface source. Maintenance and repair costs for onfarm irrigation systems in the West totaled nearly \$660 million (or \$20 per irrigated acre). Irrigation labor costs totaled about \$870 million (\$749 million for hired labor and \$121 million for contract labor). Hired labor averaged about \$33 per irrigated acre, while contract labor averaged \$20 per acre. In addition, irrigators using off-farm water supplies paid over \$671 million for purchased water from irrigation districts and other off-farm water suppliers. Purchased water costs across the West averaged about \$66 per irrigated acre, or \$24 per acre-foot of water. However, total variable irrigation costs can vary significantly across water sources. In 2008, variable irrigation costs across the West averaged about \$91 per acre for a farm using onfarm surface water, \$129 per acre for a farm pumping groundwater, and \$144 per acre for a farm pumping purchased surface water and using contract labor. In the 31 Eastern States, average variable irrigation costs ranged from \$65 to \$75 per acre. Average costs were lower in Eastern States because groundwater pumping depths are generally shallower and purchased-water costs averaged less than \$10 per acre, compared with \$66 per acre in the West (purchased water from off-farm sources account for less than 4 percent of irrigation water supplies in Eastern States).

How Efficient Is Irrigated Agriculture?

Prior to the 1970s, gravity-fed furrow and flood irrigation systems were the dominant production systems for irrigated crop agriculture. By 1978, sprinkler irrigation, including center-pivot systems, accounted for about 35 percent of crop irrigation in the Western States. Virtually all of this transition involved adoption of high-pressure sprinkler irrigation. While the center-pivot system improved field irrigation efficiency, water conservation was not the primary motivation for its widespread adoption. Other factors, such as yield enhancement from uniform water application and irrigation's expansion into productive lands that were not suitable for a gravity system due to topography, soils, or distance from traditional riparian boundaries, were the primary drivers behind the early transition from gravity-flow irrigation to center-pivot sprinkler irrigation.

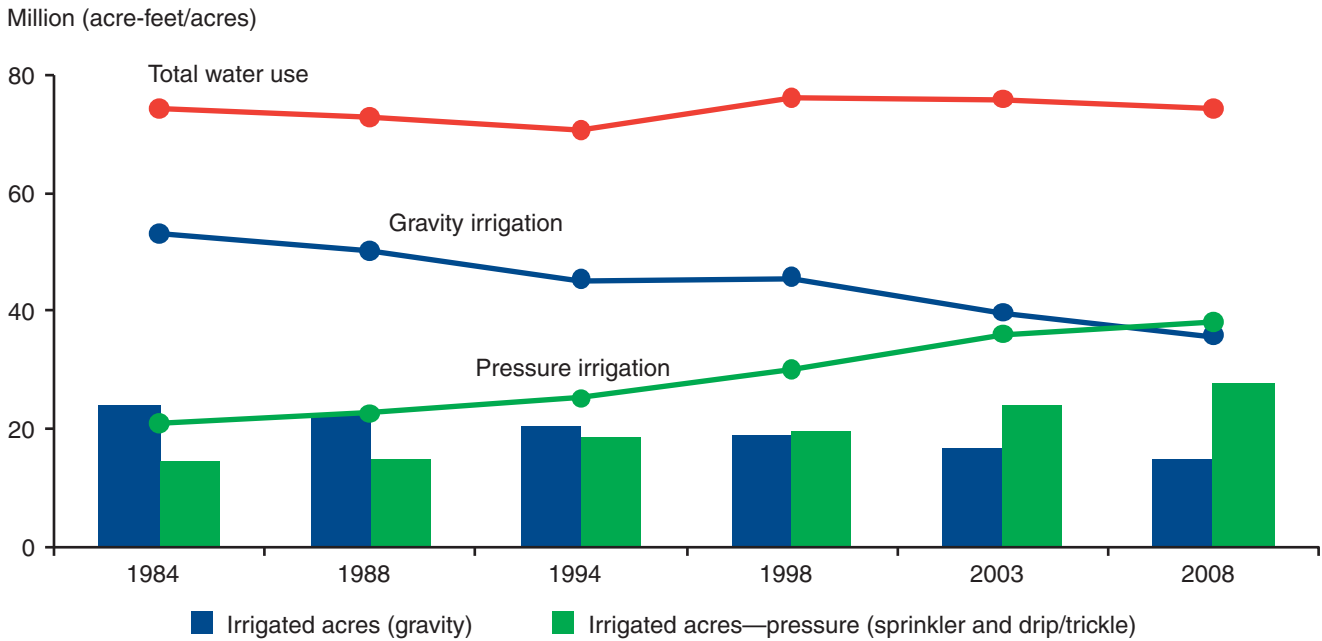
The expansion of irrigated crop agriculture, along with increasing water demands from nonagricultural users, significantly intensified the competition for available water resources. At the same time, large-scale water supply enhancement was becoming more restricted for fiscal and environmental reasons. Water conservation in irrigated agriculture became an increasingly important focus of water policy to address water allocation concerns. Various water policy analyses as early as the late 1960s recognized the merits of new regulatory, conservation, and water market policies designed to mitigate water resource allocation conflicts (Gardner and Fullerton, 1968; Hamilton et al., 1989; Hornbaker and Mapp, 1988; Howe, 1985; Martin, 1986; Moore, 1991; Schaible, 1997 and 2000; Peterson et al., 2003; Kim et al., 1989; Schaible and Aillery 2003). At the same time, producers receiving assistance from Federal and State resource conservation programs adopted more efficient irrigation systems to improve irrigation returns, enhance the health and productivity of their resource base, and ensure a more sustainable future for their livelihoods.

Adoption of more efficient irrigation systems and water management practices has been examined extensively, particularly within the 17 Western States (Schaible and Aillery, 2006; Schaible, 2004; Schaible et al., 2010). Figure 12 illustrates that between 1984 and 2008 a substantial shift has occurred across the Western States away from gravity irrigation to pressure irrigation systems. In 1984, for example, 71 percent of all crop agricultural water in the West was applied using gravity irrigation systems. By 2008, operators used gravity systems to apply just 48 percent of water for crop production, while pressure irrigation systems accounted for 51.5 percent, or an increase of 23 percentage points from 1984. By 2008, much of the acreage in more efficient pressure irrigation systems included drip, low-pressure sprinkler, or low-energy precision application systems. Improved pressure systems contributed to reduced agricultural water use, as fewer acre-feet were required to irrigate a greater number of acres using these systems. From 1984 to 2008, total irrigated acres across the West increased by 2.1 million acres, while total agricultural water applied declined by nearly 100,000 acre-feet.

Onfarm crop irrigation efficiency is measured as the fraction of applied water beneficially used by the crop, including the quantity of water required for crop ET (consumptive use) and water to leach salts from the crop root zone (Howell, 2003; Burt et al., 1997).²⁵ Water applied to crops but not used for

²⁵This definition of crop irrigation efficiency is conceptually consistent with Howell's (2003) "seasonal irrigation efficiency" and the "irrigation efficiency" (IE) performance indicator presented by Burt et al. (1997). Depending upon the crop and region (and consistent with both references cited), crop beneficial use may also include water for cooling or frost protection of plants, seed bed preparation, enhancement of seed germination, and to meet ET requirements for plants beneficial to the crop, such as for herbaceous windbreaks and cover crops.

Figure 12
Trends in irrigated acres and water applied, for Western States, 1984-2008



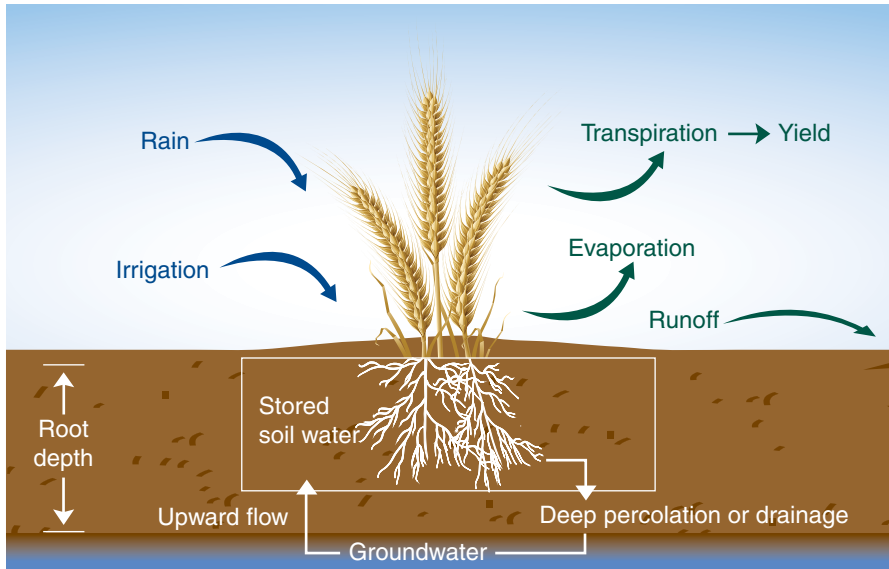
Source: USDA, Economic Research Service calculations based on USDA, National Agricultural Statistics Service, 1984, 1988, 1994, 1998, 2003, and 2008 Farm and Ranch Irrigation Survey data.

beneficial purposes is generally regarded as field loss, including water lost through excess evaporation and transpiration by noncropped biomass as well as surface runoff and percolation below the crop-root zone. Some portion of water loss to surface runoff and deep percolation may eventually return to the hydrologic system through surface return flow and/or aquifer recharge and may be available for other economic and environmental uses.

Improving onfarm irrigation efficiency, while generally recognized as conserving water on the farm, may or may not conserve water within the watershed or river basin. What happens to irrigation water that leaves the farm (i.e., water not beneficially consumed through crop production) and its ultimate impact on local or regional water supplies depend on the many factors that influence the hydrologic water balance for the watershed or river basin. Water balance accounts for where all the water within a watershed (or river basin) comes from and where it goes (fig. 13) and is significantly influenced by soils, plants, climate, water source, topography, and hydrologic characteristics both on and off the farm. The literature indicates that if conserved water at the watershed or river basin level is the important policy issue, then water conservation programs that emphasize onfarm irrigation efficiency must consider the fate of applied irrigation water in a regional water-balance context.

Several recent research papers discuss situations where improved onfarm irrigation efficiency *may or may not* contribute to watershed or river basin water conservation (Clemmens et al., 2008; Evans and Sadler, 2008; Sadler et al., 2005; Fereres and Soriano, 2007; Geerts and Raes, 2009; CIT, 2011). The conservation potential of improved irrigation efficiency reflects the share of field losses that are “irrecoverable” for additional uses in the basin

Figure 13
Fate of irrigation water



Source: Raymond J. Supalla, University of Nebraska – Lincoln, Agricultural Economics Department.

(e.g., agricultural and nonagricultural diversions and environmental flows) or otherwise unusable (or detrimental) due to impaired water quality. These studies suggest that improved onfarm irrigation can conserve water beyond the farm by:

1. Reducing unnecessary evaporation and unwanted transpiration, particularly by weeds and other noncropped biomass within waterlogged parts of irrigated fields, along water supply ditches and canals, and within and along irrigation drainage pathways;
2. Improving rainfall use with precipitation capture and moisture retention techniques (e.g., land grading, snow fences, plant-row mulches, and furrow diking techniques);
3. Reducing deep percolation water that becomes severely degraded in quality or is uneconomic to recover;
4. Reducing field runoff that is lost to the hydrologic system (i.e., runoff water that is not reusable because of salinization or entry to a saline body);
5. Reducing crop ET requirements associated with downstream irrigated agriculture (i.e., by reducing saline return flows, which allows downstream irrigators to reduce their salt leaching requirements); and
6. Reducing normal crop ET associated with crop stress under deficit irrigation (i.e., the irrigator intentionally provides the crop with less than its full ET requirement, resulting in reduced yield but higher net economic returns).

The research also indicates that, in many cases, conserved water to augment water supply in the watershed or river basin may not be the primary policy concern. Water conservation programs may also focus on enhancing the

viability and sustainability of the regional agricultural economy, improving the quality and availability of water supplies locally, improving the quality of return flows, and reducing environmental degradation of existing regional supplies. Numerous USGS National Water-Quality Assessment studies have identified irrigated agriculture as a key contributor to many of the Nation's degraded surface water bodies and groundwater aquifers because irrigation often makes heavier use of agricultural chemicals and because excess irrigation increases the hydrologic transport of agricultural chemicals, salts, and other soil-based chemicals potentially detrimental to water-based ecosystems (USGS, 2011). Thus, without adding to regional water supplies, water conservation programs encouraging improved onfarm irrigation efficiency may purposefully serve local and regional economic, water-quality, and environmental goals that contribute to farmer and societal welfare, improve fish and wildlife habitat, and reduce ecosystem and human health risks associated with environmental pollution.

The potential for continued improvement in onfarm irrigation efficiency to contribute to water-conservation program goals relies a great deal on how efficient U.S. irrigated agriculture is today. Because actual irrigation water use is rarely measured and actual consumptive use can vary significantly depending on agri-climatic conditions, the efficiency of irrigated agriculture (based on the irrigation efficiency definition discussed earlier) cannot be readily measured. An alternative measure of the relative efficiency of irrigated agriculture demonstrated in Schaible (2004) is based on the relative shares of irrigated acres where water is applied using more efficient (improved) irrigation systems, determined separately for gravity and pressure-sprinkler systems.

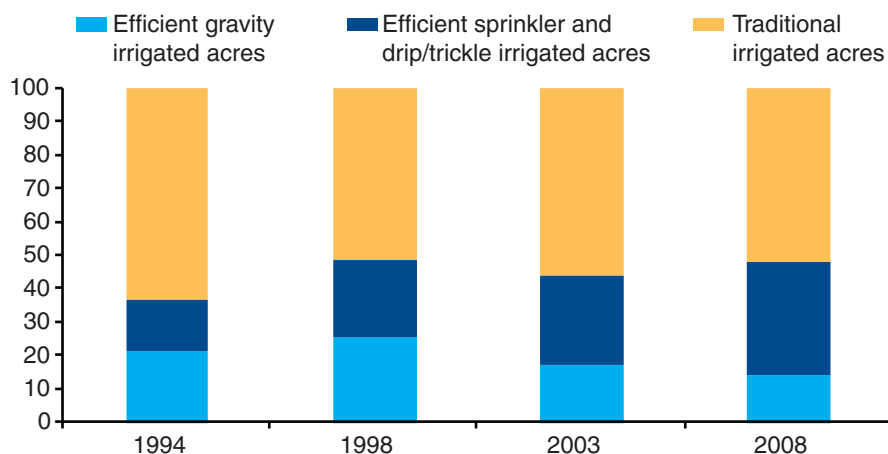
Using farm-level data from USDA's Farm and Ranch Irrigation Survey (FRIS) (USDA/NASS, 1994-2008), we categorized irrigated acres as either "traditional" or "more efficient" irrigation. More efficient gravity irrigation includes furrow gravity irrigated acres using an above- or below-ground pipe or a lined open-ditch field water-delivery system, plus acres in flood irrigation (between borders or within basins) on farms using laser-leveling and pipe or lined open-ditch field water-delivery systems. More-efficient (improved) pressure-sprinkler irrigation includes acres irrigated using either drip/trickle systems or lower pressure-sprinkler systems (pressure per square-inch (PSI) <30). Both improved gravity and pressure-sprinkler irrigation systems increase the uniformity of water distribution across a field, reduce field runoff and aquifer-seepage losses, reduce evaporation losses, and enhance crop yields.

Figure 14 illustrates the use of more efficient irrigation (separately for gravity and pressure-sprinkler systems) as a percent of total acres irrigated for the 17 Western States for 1994, 1998, 2003, and 2008. Between 1994 and 1998, the share of Western irrigated acres using improved gravity-flow systems increased from 21 to 25 percent. During the same time period, the share of irrigated acres using improved pressure-sprinkler irrigation also increased and accounted for about 23 percent of total irrigated acres in 1998. Thus, more efficient irrigation in 1998 (based on a physical system-based definition, unadjusted for levels of onfarm water management) accounted for about 49 percent of irrigation in the West. From 1998 to 2008, however, the share of gravity-flow irrigated acres using improved gravity systems declined. At the

Figure 14

Share of irrigated acres in the 17 Western States, by system type, 1994-2008

Percent of total irrigated acres



Notes: More efficient gravity irrigation includes furrow irrigated acres using above- or below-ground pipe or a lined open-ditch field water-delivery system, plus acres in flood irrigation (between borders or within basins) on farms using laser-leveling and pipe or lined open-ditch field water-delivery systems. More efficient pressure-sprinkler irrigation includes acres using either drip/trickle systems or lower pressure-sprinkler systems (pressure per square-inch (PSI) < 30). The remaining irrigated acres were categorized as using "traditional" irrigation systems.

Source: USDA, National Agricultural Statistics Service, 1994, 1998, 2003, and 2008 Farm and Ranch Irrigation Survey.

same time, improved pressure-sprinkler irrigated acres continued to increase, although at a slower rate than in the earlier period. These shifts likely suggest that a slowing of the transition from traditional gravity-flow irrigation to improved pressure-sprinkler irrigation may be attributable to thresholds beyond which conservation policy incentives for gravity-to-sprinkler system transfers may be less effective.²⁶ While substantial technological innovation has already occurred in western irrigated agriculture, significant room for improvement in farm irrigation efficiency still exists; traditional gravity or less efficient pressure-sprinkler systems still account for over 50 percent of irrigated acres. The historical transitions suggest that, while western irrigated agriculture is on a path toward greater sustainability, further progress will likely be needed as water demand and supply conditions change.

Similar conditions exist for irrigated agriculture across the 31 Eastern States. More efficient pressure (sprinkler) and gravity systems account for 52 percent of total farm irrigated acres in the Eastern States. But the remaining 48 percent of eastern irrigated acres are irrigated with traditional, less efficient systems. For the 31 Eastern States, however, improved gravity systems (at 32 percent of total irrigated acres) play the dominant role among more efficient irrigation systems relative to the West, where improved pressure (sprinkler) systems account for more than 30 percent of irrigated acres. This regional difference should not be surprising given the predominance of gravity irrigation across the Eastern States.²⁷

Despite the increased use of more efficient irrigation systems, pressures to reallocate agricultural water supplies among competing demands continue to impact the sector. Adopting more efficient physical systems alone may

²⁶For some producers, irrigation technology is considered a quasi-fixed input because various barriers (e.g., limited producer management skills, lack of financial resources, producer age, farm size, unique soil or agri-environmental conditions, or other reasons) discourage adoption of improved irrigation technologies. For example, high mountain-meadow pastures are often irrigated with gravity-based, unlined ditch water-delivery systems. With a high-priority water right and relatively low water costs, such producers are unlikely to alter their irrigation technology without increased incentive to do so (Schaible et al., 2010).

²⁷While irrigation with gravity systems occurs in most Eastern States, 5 States (Arkansas, Florida, Louisiana, Mississippi, and Missouri) account for 98 percent of all gravity-irrigated acres within the 31 Eastern States. Arkansas alone accounts for 53 percent of gravity-irrigated acres in the Eastern States. These 5 States account for 69 percent of total irrigated acres for the Eastern States.

not be enough in the face of greater demands placed on increasingly scarce water resources, especially with new demands from climate change and an expanding energy sector. The sustainability of irrigated agriculture may depend increasingly on expanded adoption of more efficient irrigation “production systems” (Evans and Sadler, 2008; Sadler et al., 2005; Clemmens et al., 2008). These production systems could involve a continued shift from traditional, less efficient gravity/sprinkler irrigation to the more efficient irrigation application systems, but with greater reliance on “within-system” water management improvements that increase overall production efficiency beyond that attainable with an improved gravity or pressure-sprinkler application system alone.²⁸

To increase the efficient use of water resources, irrigation production systems could incorporate more intensive use of infield water management practices (e.g., soil- or plant-moisture sensing devices, commercial irrigation scheduling services, or computer-based crop-growth simulation models) that help farmers decide when to irrigate and how much water to use by crop growth stage (Schaible et al., 2010). Improved water management practices can help producers maximize the economic efficiency of their irrigation systems and the potential for real water savings through reduced system losses and managed reductions in crop consumptive use.

For irrigated agriculture, in general, and for gravity irrigation, in particular, survey data suggest that producers do not make widespread use of less water-intensive infield water management practices. Across the West, producers using gravity-flow irrigation tend to give more emphasis to such practices as reduced irrigation set times, alternate furrow irrigation (for row crops), and end-of-field dikes to restrict field runoff (table 4). Other less water-use intensive management practices for gravity systems have declined in use or have received little producer attention. Use of tailwater pits for onfarm water reuse (reducing the need for additional withdrawals) has declined across gravity irrigation, from 22 percent in 1994 to 8 percent in 2008, partly in response to irrigation application improvements that limit field runoff. Laser-leveled acres on gravity irrigated fields declined from 27 percent of acreage in 1998 to 16 percent in 2008.

By 2008, less water-intensive gravity-management practices, such as special furrowing techniques, shortened furrow lengths, and polyacrylamide (PAM), were applied on a relatively small portion of gravity-irrigated agriculture in the West. Less interest in these practices may reflect their expected economic impact at the farm level, either through increased costs for land preparation or for specialized furrow-management equipment, particularly when expected profit margins are low. Across the Eastern States, however, producers tend to give more emphasis to alternate row irrigation and laser-leveling of fields to improve water management on gravity-irrigated acres (accounting for 11 and 22 percent of gravity irrigated acres, respectively). As in the West, use of efficiency-enhancing gravity water management practices accounts for a relatively small portion of gravity irrigated acres.

Despite technological advances in crop and soil moisture sensing, irrigators across the United States continue to depend heavily on traditional decision-making methods in deciding when to irrigate a crop and by how much. In the West, most producers generally irrigate based on the visible “condition

²⁸The sustainability of irrigated agriculture also could be enhanced through continued research and development of crop cultivars with improved tolerance to drought, heat, and salts, as well as shorter growing seasons. This particular issue is beyond the focus of this report.

Table 4
Water management practices in the 17 Western States, 1984-2008

Methods/practices	1984	1988	1994	1998	2003	2008
Total number of irrigated farms	179,473	180,525	149,351	147,090	174,936	169,985
Total gravity irrigated acres	24,084,966	22,731,136	20,344,444	19,164,703	16,491,380	15,023,307
Methods used in deciding when to irrigate:	<i>Percent of irrigated farms</i>					
Use of any method (including one or more of the decision methods below):	0.96	0.94	0.96	0.99	1.00	1.00
Condition of the crop	0.26	0.69	0.66	0.70	0.77	0.84
Feel of the soil ¹	0.40	0.36	0.37	0.40	0.34	0.42
Use of soil moisture sensing devices	0.08	0.08	0.09	0.08	0.07	0.09
Use of commercial scheduling services	0.03	0.05	0.03	0.04	0.07	0.09
Use of media reports on daily crop ET	0.04	0.04	0.03	0.05	0.08	0.10
Based on scheduled water delivery "in turn" to the farm	0.13	0.13	0.18	0.12	0.15	0.14
Based on a calendar schedule	0.18	0.18	0.20	0.20	0.21	0.27
Use of computer simulation models	NA	NA	0.03	0.01	0.00	0.01
Use of plant moisture sensing devices	NA	NA	NA	NA	0.02	0.02
Irrigate when the neighbors do	NA	NA	NA	NA	0.07	0.07
Water management practices used with gravity-flow irrigation systems:	<i>Percent of gravity-irrigated acres</i>					
Tailwater pits	NA	0.20	0.22	0.12	0.08	0.08
Surgeflow/cablegation irrigation ²	NA	0.05	0.04	0.04	0.02	0.02
Special furrowing techniques ³	NA	0.12	0.12	0.06	0.06	0.05
Reducing irrigation set times or number of irrigations	NA	NA	0.13	0.13	0.15	0.15
Using alternate row irrigations	NA	NA	0.17	0.15	0.12	0.10
Use of polyacrylamide (PAM)	NA	NA	NA	0.02	0.02	0.02
Restricting runoff by diking end of field	NA	NA	NA	NA	0.13	0.15
Use of mulch or other type of row cover	NA	NA	NA	NA	0.01	0.01
Laser-leveled acres	NA	0.10	0.21	0.27	0.16	0.16

ET=Evapotranspiration.

NA = Not Available. FRIS surveys did not collect data for all decision methods or water management practices for all years.

¹The practice of evaluating when to irrigate by physically feeling the soil to estimate its moisture content.

²Surge flow is an adaptation of gated-pipe systems whereby water is delivered to the furrow in timed releases controlled by a valve. Furrows are alternately wetted and allowed to dry. As the soil dries, the soil surface forms a water seal permitting the next surge of water to travel further down the furrow with less upslope deep percolation. Cablegation is a gated-pipe system in which a moveable plug is allowed to slowly pass through a long section of gated pipe, with the rate of movement controlled by a cable and brake. The system is designed such that water flow will gradually cease flowing into the first rows irrigated after the plug has progressed sufficiently far down the pipe. Improved water management is achieved by varying the speed of the plug, which controls the timing of water flows into each furrow.

³Special furrowing techniques may include using wide-spaced bed furrows, compact furrowing, furrow diking, or shortening of the furrow length.

Source: USDA, National Agricultural Statistics Service, 1984, 1988, 1994, 1998, 2003, and 2008 Farm and Ranch Irrigation Survey.

of the crop” or by “feeling the soil” for soil-moisture content, or irrigation may be based on a calendar schedule (which can be influenced by labor availability from local labor markets) or an “in-turn” (fixed rotation) delivery schedule for water supplied to the farm (see table 4). For 2008, fewer than 10 percent of irrigators throughout the West used soil- or plant-moisture sensing devices or commercial irrigation scheduling services. Fewer than 2 percent of irrigators used computer-based simulation models to evaluate crop irrigation requirements based on consumptive use needs by crop-growth stage and local weather conditions. Low adoption rates may be due to the fact that these practices are much more human-capital and management intensive than traditional water-application decision tools. These more sophisticated tools may require more extensive technical training and support to increase adoption rates.

Similar relationships exist for the Eastern States, except that irrigation decisions generally are not based on water delivered within a fixed rotation to the farm. While 14 percent of irrigators in the West reported that water delivered within a fixed farm rotation influenced their decisions on when to irrigate, less than 1 percent of irrigators in the Eastern States relied on this arrangement. The decisionmaking process varies by region and reflects the fact that, in the West, 33 percent of irrigated acres used water from off-farm sources, generally from irrigation districts, while in the East, less than 4 percent of irrigated acres used off-farm water sources.

According to the 2008 FRIS, at least half of irrigated crop acreage across the United States continues to be irrigated with less efficient irrigation application systems and most irrigators do not make use of less water-intensive onfarm water management practices. Our findings suggest that, particularly for the West, given the increasing water demand pressures from competing uses, the potential for reduced water supplies and increased evaporation losses associated with climate change, a sustainable future for irrigated agriculture may require wider adoption of more efficient irrigation practices.

According to the National Research Council report, *Toward Sustainable Agricultural Systems in the 21st Century* (NRC, 2010), and the recent USDA Research, Education, and Economics Action Plan (USDA/REE, 2012),²⁹ achieving a more sustainable future for irrigated agriculture through agricultural water conservation involves three elements:

- Continue to encourage adoption of high-efficiency irrigation application systems;
- Place greater emphasis on adoption of more efficient irrigation production systems (a farming systems approach) that better manage when and how much water is applied at the field level, enhancing producer ability to respond to water shortages as well as promote agricultural water conservation through deficit irrigation while improving farm profits; and
- Better integrate onfarm water conservation with watershed-level water management mechanisms that help facilitate optimal allocation of limited water supplies among competing demands (e.g., use of conserved water rights, drought-year water banks, water-option markets, contingent water markets, reservoir management, irrigated

²⁹“Sustainable agriculture” as a USDA policy goal was initiated with the Food, Agriculture, Conservation, and Trade Act of 1990, with the key objective to “protect and enhance America’s water resources.” USDA’s Strategic Plan for FY 2010-15 highlights the importance of using farm-level, watershed, and institutional measures as a strategic means to meet this goal (USDA, 2012).

acreage and groundwater pumping restrictions, and irrigated acreage retirement).

The box “Irrigation Production Systems and Agricultural Water Conservation” expands upon the concept of accounting for basin-level water balance by considering the fate of farm-level water savings/losses and strategies underway to improve onfarm irrigation water-use efficiency and integrate water conservation and watershed water-management tools.

Watershed-level water management tools can create more efficient water allocations by encouraging water-resource stakeholders to recognize the opportunity value of water across competing uses and by facilitating water transfers through varying degrees of market-based trading and reallocation schemes. USDA presently participates in watershed-scale agricultural water conservation and water-management activities through Federal, State, and local partnership agreements established under its Agricultural Water Enhancement Program (AWEP). With the 2008 Food, Conservation, and Energy Act’s establishment of AWEP, USDA’s water conservation program was effectively extended to embody a focus on farms as well as on a watershed/regional/institutional conservation. Since 2009, USDA’s Natural Resources Conservation Service, (NRCS) has entered into 101 AWEP partnership agreements designed to enhance agricultural water conservation.³⁰ AWEP allows USDA to integrate onfarm water conservation with institutional and watershed water-management tools to enhance water conservation objectives at a “landscape scale,” while leveraging financial support from other Federal, State, and local organizations. The box, “Institutional Tools for Water Management,” presents examples of policy approaches being used to encourage and enhance agricultural water conservation.

³⁰With the AWEP, under the Environmental Quality Incentives Program (EQIP), USDA’s NRCS presently manages multi-year watershed-level water conservation partnership agreements with State, local, irrigation district, federally recognized Indian Tribes, and nongovernmental organizations. The complexity of these partnerships can range from providing producers financial assistance to convert from gravity irrigation to low-pressure sprinkler irrigation, to using irrigated acreage and water-use restrictions and conserved water for instream flow uses and managed drought-year water banks. NRCS partnership agreements and water management mechanisms can vary significantly across watersheds and States. For a description of AWEP partnership agreements, see http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/programs/?&cid=nrcs143_008334.

Irrigation Production Systems and Agricultural Water Conservation

Agricultural water conservation has long been recognized as key to providing water resources to meet the increasing demands of competing uses. Historically, promoting producer adoption of irrigation technologies that increase farm-level irrigation efficiency has been a principal policy focus. Through the use of conservation-incentive programs, Federal and State agencies have funded improvements in irrigation system efficiency to help meet the needs of competing water demands. In recent years, however, the appropriateness of this policy approach has been challenged. Concerns have been raised about the effect of irrigation technology adoption on irrigation consumptive water use and the amount of water actually “conserved.”

Researchers believe that public promotion of more efficient irrigation technologies can unintentionally increase irrigated crop consumptive water use at the basin level by encouraging wider adoption of crop irrigation and/or the production of more water-intensive crops (Whittlesey and Huffaker, 1995; Huffaker and Whittlesey, 2003; Ward and Pulido, 2008; Clemmens et al., 2008; Evans and Sadler, 2008). This policy concern suggests that improving irrigation efficiency may not always “conserve” water for off-farm uses. The potential of irrigation efficiency improvements to achieve water savings within a basin depends partly on the nature of irrigation system losses and rates of irrigation return flow to surface streams and aquifers. Potential water savings also depend on whether water-use efficiency gains are offset by increases in crop consumptive water use. Where return flows are high from irrigation systems, real water conservation may require reduced crop consumptive water use within the basin.

Improved Technology Alone May Not Be Enough. Producer adoption of more efficient irrigation technology may increase agricultural water consumption in several ways.

1. More efficient irrigation systems allow the producer to reduce the quantity of water applied to a field, often through improved uniformity of field-water distribution and timing of water applications to meet crop growth-stage requirements. These improvements may also result in higher crop yields, which generally increase crop consumptive water use.
2. In the absence of defined “conserved” water rights, water savings from irrigation efficiency improvements on one field may be applied to additional crop acreage under irrigation. Unless restricted, “water spreading” over an expanded acreage base generally increases aggregate agricultural water consumption.
3. Improved irrigation technologies can alter the economics of irrigation enough to entice producers to adjust traditional cropping patterns, potentially shifting to more water-intensive irrigated crops. In the High Plains, for example, higher yields and reduced irrigation pumping costs with improved irrigation efficiency have prompted a shift from irrigated wheat and sorghum production to increased acreage in irrigated corn. These types of cropping pattern adjustments may increase aggregate crop consumptive water use.

Improved irrigation efficiency can also have off-farm implications. Specifically, upstream water savings may be claimed by downstream (junior water-right) irrigators, increasing basin-wide agricultural consumptive water use. Where

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Irrigation Production Systems and Agricultural Water Conservation (continued)

seasonal instream water flows are limiting, increases in crop consumptive water use may adversely impact water allocation objectives for environmental and other purposes at the basin level. Similarly, groundwater savings from reduced irrigation pumping requirements under high-efficiency systems may be offset by expanded aquifer withdrawals for additional irrigated acreage and other purposes off the farm.

Benefits of Technological Improvements. While the effects of irrigation efficiency on crop consumptive use and net water savings are an important policy concern, investment in more efficient onfarm irrigation technologies has additional benefits.

1. Improved irrigation technologies are generally productivity enhancing, requiring less land and water inputs for a given level of yield.
2. Enhanced irrigation efficiency produces onfarm water savings through reduced applications that also reduce farm water costs (Evans and Sadler, 2008; Sadler et al., 2005; Fereres and Soriano, 2007; Geerts and Raes, 2009). Higher productivity and reduced water costs are important to the economic viability of a sustainable irrigated agriculture sector over the long term.
3. Improved onfarm irrigation efficiency generally results in significant water quality and environmental benefits (Huffaker, 2010; Kim et al., 2000; Schaible and Aillery, 2003; Weinberg et al., 1993). Efficient irrigation “production systems” allow producers to improve their nutrient management practices through chemical application efficiencies, reduced soil erosion runoff, improved salinity control, and improved drainage water quality. Improving onfarm irrigation efficiency also reduces nutrient loads, pesticides, and trace elements in irrigation runoff to surface waters, as well as leaching of agrichemicals into groundwater supplies, producing off-farm benefits for ecosystem habitats, endangered species recovery, biodiversity, and human health.

Broadening Policy Focus To Achieve Conservation Goals. Public water conservation programs that encourage producer adoption of efficient “irrigation production systems,” integrated within basin-level institutional water management initiatives (e.g., conserved water-right provisions, groundwater withdrawal restrictions, water banks, and option and contingent water markets), could enhance the potential for real agricultural water conservation. Integrated farm and basin-level institutional conservation initiatives could encourage both irrigators and conservation program managers to consider the alternative opportunity values of water across competing demands, improving allocation of scarce water resources. In doing so, irrigation efficiency improvements, as part of a broader basin-level conservation plan, may be combined with other practices, such as deficit irrigation, acreage idling, and off-farm water transfers, that reduce crop water consumption in water-deficit years while allowing producers to maximize farm income. Through the adoption of highly efficient irrigation production systems, in combination with water allocation frameworks that encourage producers and program managers to jointly consider the opportunity values of water within the basin, the overall efficiency in water allocations can be improved while enhancing real agricultural water conservation.

Institutional Tools for Water Management

Agricultural water conservation can enhance crop production and farm income, as well as water resources for competing demands, where institutional provisions provide appropriate incentives for the allocation of conserved water. USDA's Agricultural Water Enhancement Program—under the Environmental Quality Incentive Program (EQIP)—is one approach within a broader partnership-based institutional framework that provides financial assistance to agricultural producers to implement agricultural water enhancement activities on agricultural land to conserve surface and groundwater and to improve water quality. Various institutional provisions at the Federal and State level help promote potential water savings from onfarm investments in improved irrigation production systems. Integrating onfarm water conservation programs with institutional water management mechanisms can encourage the reallocation of conserved water to meet off-farm uses for environmental flows and other higher valued water demands, both agricultural and nonagricultural. Examples of how onfarm water conservation has been integrated with institutional water management measures include:

- **EQIP financial assistance provisions.** By allocating Federal funds for irrigation technology investments, EQIP program managers at the State (or sub-State) level may assign priority to contract offers demonstrating net water savings at the farm level. Financial assistance for irrigation technology improvements may also be combined with environmental measures that limit agricultural water withdrawals. For example, in a special EQIP project in south-central Nebraska where groundwater pumping has affected Platte River flows for endangered species, financial assistance for conversion to high-efficiency sprinkler systems was tied to restrictions on irrigated acreage expansion.
- **Groundwater management.** States may enact groundwater management regulations that promote adoption of improved irrigation technology. In Arizona, where groundwater withdrawals for agricultural production have resulted in significant water-table declines, groundwater management areas have been established to limit groundwater overdraft. Under the groundwater management provisions, agricultural water conservation programs were established for designated groundwater management areas. Irrigation withdrawals for farms within these areas are tied to successively higher irrigation efficiency levels. Compliance with an approved set of best management practices for irrigated production may be accepted in lieu of fixed groundwater withdrawals.
- **Environmental flow regulations.** Federal and State regulatory requirements for environmental flows may be combined with policy initiatives for water conservation. The Central Valley Project Improvement Act (CVPIA) of 1992, which reallocated farm water deliveries to meet instream flow requirements, mandated water conservation programs at the irrigation district level. In 2001, severe drought in the Klamath River Basin (California and Oregon) prompted Federal regulatory restrictions on agricultural water diversions to ensure flows for endangered fish species. The Federal action resulted in a special USDA EQIP funding allocation to support improved irrigation systems in the Klamath River Basin under the 2002 Farm Act.

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Institutional Tools for Water Management

(continued)

- **Incentive pricing for surface water.** Current prices for surface irrigation water may not reflect the market value of water. In many cases, water charges are tied to some portion of the capital and maintenance costs of the delivery system and often do not reflect the value of water in irrigation or its opportunity cost in other uses. With tiered pricing for surface water deliveries, per-unit costs increase (in a stepped fashion) with the volume of water delivered. The CVPIA established tiered water pricing for agricultural diversions at the irrigation district level in California's Central Valley Project. Individual irrigation districts may decide whether or not to implement tiered pricing (using a modified schedule or alternative rate to cover the increased costs of water they receive from the Bureau of Reclamation project) for their respective producers (CBO, 1997). Producers may lessen their average per-unit water charge by adopting higher efficiency irrigation systems that reduce total farm water diversions.
- **Water markets.** Water markets can improve the allocation of water among competing economic uses by facilitating the voluntary transfer of water to higher valued uses under sale or lease agreements. Water markets can encourage investment in more efficient irrigation technologies through improved market signals on the value of water. Water savings through irrigation system upgrades at the farm level may be available for transfer off the farm. Similarly, farmers investing in irrigation improvements may value the additional certainty of water supplies available through the market. States can help protect environmental services through laws governing water transfers. In Oregon, for example, irrigators may transfer water made available through conservation as long as 25 percent of water conserved is reserved for instream uses.
- **CREP land retirement.** Under USDA's Conservation Reserve Enhancement Program (CREP), the Federal Government may partner with States, tribes, local governments and private entities to idle irrigated cropland under long-term lease agreements. CREP partnerships provide greater enrollment incentives than what currently exists under a Conservation Reserve Program (CRP) general signup—USDA's primary land retirement program. Under CREP contracts, USDA offers higher payments tied to irrigated rental rates, while partners provide funding for additional expenses, such as permanent easements or retirement of water rights. Today, CREP projects in several Western States (Nebraska, Colorado, Idaho, and Kansas) target agricultural water conservation in critical watersheds. The projects are designed to reduce consumptive use of surface and groundwater through retirement of irrigated land and accompanying restrictions on water withdrawals, and they are intended to lessen the effect of water-supply shortfalls on water users and natural systems during periods of sustained drought. Related project goals involve enhanced water quality and terrestrial habitat through establishment of vegetative cover and restoration of aquatic systems through reestablishment of flow volumes in river systems and adjoining wetlands.

Irrigation Investments: Decision Factors, Types, Purposes, and Funding Sources

While the need for continued improvements in water-conserving production systems in U.S. irrigated agriculture is well established, water-use efficiency gains depend on irrigation investment decisions in the private farm sector. Various factors influence the adoption of more efficient irrigation systems and water management practices, and their relative importance in the technology selection decision varies across locations and farm types, ultimately affecting investment expenditures and funding sources in the U.S. irrigated sector.

Factors Affecting Irrigation Technology Investment Decisions

Potential gains in onfarm water-use efficiency, and resulting crop yield and/or input use benefits, vary across systems and resource settings. Survey data suggest that resulting income gains from irrigation technology adoption drive most investment decisions. According to the 2008 FRIS, 59 percent of U.S. survey respondents who invested in system upgrades reported reductions in applied water, and 60 percent reported improvements in crop yield and quality as a direct result of making recent irrigation investment decisions (table 5). Reductions in irrigation-related energy and labor costs were identified by 46 and 41 percent of respondents, respectively. Other reported investment benefits included reductions in soil erosion, fertilizer and pesticide loss, and drainage runoff. Most farmers across the United States seemed to be similarly motivated when making irrigation investment decisions, although farms in the Eastern States placed a slightly higher emphasis on improving irrigated crop yield and quality.

The suitability of irrigation system investments often depends on the physical characteristics of the land (Caswell and Zilberman, 1985; Negri and Brooks, 1990). Improved gravity-flow systems perform best on fields with low slope and higher quality soils with low water-infiltration rates. Sprinkler systems have an advantage for use on nonuniform-shaped fields with greater slope and soils with higher infiltration rates. Land quality considerations can have an impact on potential efficiency gains in water use and related energy and labor requirements.

Expanding irrigated acreage on a farm will likely involve new investment in high-efficiency irrigation systems. Similarly, a farm that reduces irrigated acreage is more likely to discontinue irrigation on acres with lower efficiency systems. Cropping decisions may also affect the types of system innovations considered. Costly irrigation innovations are less likely to be applied for lower valued hay and pasture crops. Water-use efficiency gains may be greater for crops with relatively higher water needs, such as corn, relative to less water-intensive crops, such as wheat. A crop's cultural requirements may also affect irrigation system improvement choices. Special furrow techniques that modify soil-moisture infiltration, for example, and improve the uniformity of applied water across a field are best suited to row crops, such as corn and cotton. Of survey respondents indicating barriers to practice adoption in 2008, 16 percent identified physical field conditions and cropping

Table 5
Results of irrigation system improvements and key barriers to making system improvements, 2003-08

	17 Western States	31 Eastern States	United States
Farms implementing irrigation system improvements (since 2003)	62,189	11,926	74,846
	<i>Percent</i>		
Effect of system improvements: ¹			
Improved crop yield/quality	58.7	67.6	60.2
Reduced energy costs	43.6	56.5	45.6
Reduced water applied	60.6	54.1	59.4
Reduced labor costs	42.6	34.7	41.2
Reduced fertilizer/pesticide loss	18.3	16.1	17.9
Reduced soil erosion	29.8	25.9	29.1
Reduced tailwater runoff	23.6	11.5	21.5
Farms identifying barriers to energy and/or water conservation improvements (since 2003)	107,796	22,626	131,988
	<i>Percent</i>		
Barriers to making irrigation system improvements: ¹			
Investigating improvements was not a priority	34.6	39.6	35.5
Risk of reduced yield or poorer crop quality	14.2	13.5	14.1
Physical field/crop conditions limit system improvements	17.0	10.4	15.8
Improvements will not reduce costs enough to cover installation costs	26.3	2.2	25.6
Cannot finance improvements	29.6	23.1	28.4
Landlord will not share costs of improvements	4.5	8.0	5.2
Uncertainty about future availability of water	17.0	4.8	14.8
Will not be farming long enough to justify new improvements	13.4	11.3	13.1

¹For each issue, farm respondents were allowed to select multiple response categories. Source: USDA, National Agricultural Statistics Service, 2008 Farm and Ranch Irrigation Survey, Vol. 3, Special Studies, Part 1, AC-07-SS-1, 2010, <http://www.agcensus.usda.gov>.

considerations as barriers (17 percent in the West and 10 percent in the East) (table 5).

The cost of irrigation system upgrades can be an important limiting factor in irrigation investment decisions. While new technologies offer potential long-term gains, installation of irrigation equipment often requires large capital investment as well as more onfarm management. Producers' decisions

to invest depend on whether the expected benefits of adoption outweigh expected costs, relative to production systems currently in use. According to the 2008 FRIS, 28 percent of respondents identifying barriers to conservation indicated an inability to finance improvements as a barrier to change (30 percent in the West and 23 percent in the East) (table 5). Many respondents believed that system improvements would not lower production costs sufficiently to cover costs (26 percent of all respondents). For some of these producers, long-term investment paybacks may also be viewed as overly speculative. Public financial assistance programs that support the adoption of more efficient irrigation practices reduce the effective cost borne by producers.

For some irrigators, the cost of water supplies plays a larger role in irrigation investment decisions. Incentives for water-use efficiency gains are greatest where water costs are high. High-efficiency pressurized systems, for example, are predominant in the Plains States where deep-well groundwater irrigation is predominant. In surface water supply areas, irrigators may be reluctant to invest in improved irrigation technologies where the price per unit of water is low or water is charged on a per-acre basis.³¹ Water pricing policies have been implemented for public surface-water supplies to capture capital and operation costs of the off-farm delivery system while also promoting onfarm water conservation. Under the Central Valley Project Improvement Act of 1992, for example, tiered (block-rate) pricing structures are applied to water deliveries for project contractors (irrigation districts).³² However, districts may elect to use a modified rate schedule or an alternative average rate when pricing water deliveries to farmers (CBO, 1997).

Adoption of improved irrigation systems may also occur in response to restricted water supplies. Reduced water losses under more efficient systems are intended to offset water-supply shortfalls. In California, surface water delivery restrictions under sustained drought conditions in the early 1990s prompted improvements in irrigation water-use efficiency as well as institutional adaptations in water resource allocation (Zilberman et al., 1998; CBO, 1997). In some cases, public financial support for improved irrigation practices has been contingent upon water-supply restrictions. In the Central Platte Natural Resource District of Nebraska, for example, irrigation expansion was limited under an Environmental Quality Incentives Program (EQIP) special project to support conversion from gravity to sprinkler irrigation systems (SWCS and ED, 2007).

Farmers also may be reluctant to invest in improved technologies if access to future water supplies is uncertain. In the 2008 FRIS survey, uncertainty about future water availability was identified as a barrier to technology adoption by 17 percent of irrigators in the Western States and 5 percent of irrigators in the Eastern States (table 5). Water-supply uncertainty is a particular concern for junior holders³³ of surface water rights, whose water supply fluctuates more significantly with annual variability in precipitation. These water-rights holders may face irrigation delivery cutbacks when water supply conditions fall below levels required to meet the needs of senior water right holders.

The technology adoption decisions of senior versus junior appropriators vary depending on differences in land quality and operator management skills,

³¹Schuck et al. (2005) indicated that other factors, such as recurring drought conditions, could motivate irrigators to adopt improved irrigation technologies even under low water prices.

³²For the first rate tier, a district is charged the applicable contract (subsidized) rate for the first 80 percent of water delivery, then an average of the contract and full-cost rates for water quantities between 80 and 90 percent of water delivery, and a district full-cost rate for the last 10 percent of water delivery to the district.

³³Under the "prior appropriation system," the dominant water-rights legal institution in the Western States, water allocations are based on the "priority date" of the water right, a principle generally characterized as "first in time, first in right." Each water right has a specific annual quantity with an assigned appropriation date. Water-right holders with the earliest appropriation dates (senior appropriators) generally receive their full appropriation, provided there is adequate water supply. In water-short years, users holding water rights with later appropriation dates (junior appropriators) may not receive their full appropriation or even any water at all.

uncertainty over future water prices, the level of the farm's water allocation, perceived water-supply risk, whether water markets exist, and access to market-based information among water-right holders. For example, Carey and Zilberman (2002) revealed that water markets may decrease technology adoption incentives for some farms. For farms with abundant water supplies (i.e., senior appropriators), water markets are likely to increase incentives to invest in improved irrigation systems in anticipation of marketing water savings; but for farms with scarce supplies (i.e., junior appropriators), a water market may cause a postponement of irrigation technology investments as they have the option to purchase water in the market.

In the absence of a water market, however, Carey and Zilberman determined that a farm's willingness to invest in improved technology is influenced by the size of the farm's water allocation. The authors concluded that senior appropriators without a means to market water have less incentive to adopt improved technology, while junior appropriators with reduced supply recognize that they may need to produce at reduced acreage or lower yields (deficit irrigate) with the traditional technology, prompting them to adopt more efficient systems.³⁴ This effect is likely influenced by how junior the water right and the perceived magnitude of the water-supply risk relative to the potential onfarm efficiency gain. For example, junior appropriators facing significant water-supply risk may have less incentive to adopt improved irrigation systems because the investment may too often sit idle in water-short years.

Inadequate off-farm water storage and delivery infrastructure also can represent a significant barrier to achieving maximum irrigation efficiencies through improved onfarm technologies (USDA/REE, 2004). Investment may be needed to enhance the capacity of an off-farm delivery system to supply onfarm water requirements on a more timely basis. For 2008, FRIS results indicated that 14 percent of irrigators had no choice in scheduling their irrigation because water was delivered to the farm on a fixed rotation basis via their water-delivery organization.

Irrigators also may be reluctant to adopt new technologies due to risk of unsuccessful outcomes, particularly in the short term (Harwood et al., 1999). Irrigation system upgrades are often part of a broader change in production systems. New irrigation technologies often require higher levels of information and management to achieve potential yield gains and input use efficiencies. Increased adoption of improved irrigation systems may require a commitment of public funding for technical support, demonstration projects, and information transfer.

Farm size and structure as well as demographic factors also influence farm-level irrigation system improvements. Larger farms that benefit from a stronger capital base and scale economies may be better positioned to adopt system improvements. Schaible (2004) and Schaible and Aillery (2006) reported that farm size influenced how effectively water conservation programs serve both USDA conservation and small-farm policy goals. Schaible (2004) notes that the largest 10 percent of irrigated farms in the West (farms with more than \$500,000 in sales) accounted for nearly 50 percent of total farm water applied. While relative irrigation improvement potential—the percent of irrigated acres still irrigated with traditional, less-efficient systems—is generally greater for smaller irrigated farms, larger

³⁴This would imply that, for some watersheds, a cut in irrigation water allocations may result in reduced supplies to producers using more efficient systems.

farms irrigate many more acres and account for most agricultural water use, implying a greater conservation-gain potential to meet environmental and other farm-policy goals. In addition, owner-operators may be more likely than renters to make the large capital investments necessary for improved systems. Younger farmers are more likely to recoup irrigation investments than aging farmers facing retirement. The overall health of the farm economy may also influence irrigation investments—“good times” are generally better for investments than “bad times.”

Onfarm Irrigation Investment Expenditures

The 2008 FRIS indicated a significant increase in onfarm irrigation investment expenditures relative to the 2003 survey year. Approximately \$2.15 billion was invested in irrigation systems in 2008 (beyond expenditures for maintenance and repair of \$820 million), compared with \$1.12 billion in 2003. Higher investment expenditures reflect both an increase in the number of farms reporting irrigation investments (up 22 percent) and higher average expenditures per farm (up 73 percent). Investment in irrigation system upgrades, where water conservation was identified as the principal purpose, totaled \$323 million in 2008—up by nearly 90 percent from 2003.

Table 6 shows 2008 expenditures for onfarm irrigation facilities and equipment by primary purpose for the 17 Western States, as well as totals for the Eastern States and the entire United States. New equipment for irrigation expansion accounted for about 35 percent of expenditures nationwide. New equipment expenditures accounted for a somewhat higher share in Eastern States, reflecting expansion in irrigated acreage. More than half of onfarm investment expenditures in the West was made to replace existing equipment and machinery. Farmers nationwide upgraded their irrigation facilities and equipment to improve water conservation, accounting for roughly 17 percent of onfarm irrigation investment expenditures in the West and 9 percent in the East.

Onfarm irrigation investments focus on more precise water application that satisfies crop requirements, while minimizing field losses. Upgrades in application equipment and machinery accounted for 65 percent of investment expenditures made to improve onfarm water conservation in Western States. Land leveling to improve the uniformity of applied water in gravity-flow systems accounted for an additional 21 percent of conservation expenditures. Improved onfarm water storage and conveyance systems are also important, reducing storage and conveyance losses and improving efficiency potentials for onfarm water-delivery systems. Onfarm water storage and conveyance upgrades accounted for roughly 9 percent of water conservation expenditures in the West. Computers and information systems for irrigation management represented 5 percent of water conservation expenditures. While well expenditures are not directly related to conservation, groundwater access is an important adaptation to drought risk. Well construction, including replacement and new wells, represents a significant portion of total onfarm irrigation investment expenditures. In the Eastern States, irrigators devoted nearly 67 percent of their 2008 irrigation investments to new or replacement equipment and machinery. While water conservation is important in these States, past irrigation investments in the Eastern States were generally made to maintain

Table 6
Expenditures for irrigation facilities and equipment, 2008

	Total expenditures	Average per farm	Purpose of expenditure			Source of funding assistance			
			Replacement	Water conservation	New equipment	No funding assistance	USDA's EQIP	Other USDA cost-share programs	Non-USDA cost-share programs
Types of investment: (17 Western States)	<i>\$1,000</i>	<i>Dollars</i>	<i>\$1,000</i>			<i>Number of farms</i>			
New/replacement irrigation equipment and machinery	1,098,826	18,155	629,381	175,520	293,925	60,769	2,326	864	666
New well or deepening of existing well	261,954	43,871	153,520	NA	108,434	5,913	29	30	101
New/improvement of storage and distribution systems	85,030	12,111	28,587	25,172	31,271	7,113	292	144	37
Land clearing and leveling for irrigation purposes	91,824	12,520	NA	56,499	35,325	7,520	139	125	15
Computers, control panels, and software for irrigation water management	37,451	6,262	12,183	12,295	12,973	5,973	148	103	35
All investment types;									
17 Western States	1,575,085	23,336	823,671	269,486	481,928	87,288	2,934	1,266	854
31 Eastern States	494,063	27,369	203,554	46,247	244,261	23,528	1,304	612	489
U.S. total ¹	2,149,007	23,628	1,077,192	323,083	748,732	111,317	4,240	1,878	1,343

EQIP=Environmental Quality Incentives Program, and NA = not applicable.

¹U.S. totals include statistics for Hawaii and Alaska.

Source: USDA, National Agricultural Statistics Service, 2008 Farm and Ranch Irrigation Survey, Vol. 3, Special Studies, Part 1, AC-07-SS-1, 2010, <http://www.agcensus.usda.gov/>.

crop irrigation during periods of below-normal rainfall and to expand irrigation capacity.

Sources of Onfarm Irrigation Investment Funding

Most onfarm irrigation investment in the United States is financed privately. Of farms reporting irrigation improvements in 2008, 6 percent received public financial assistance. High levels of private investment reflect both the magnitude of expenditures on replacement equipment and irrigation expansion that typically do not qualify for public assistance, and the private gains associated with irrigation investment (e.g., higher yields and input-use efficiency). Participation in public funding programs may also be limited by program funding allocations, administrative requirements for program enrollment, and payment limits to farm operators. For many irrigators, however, public programs represent an important source of funding to support adoption of more efficient irrigation systems.

The EQIP, administered by USDA's NRCS, is the Nation's primary agricultural conservation program for working farms and ranches. EQIP provides technical and financial assistance for eligible conservation practices under short-term contracts (1-10 years). Financial support for installation of structural and vegetative practices range from 50 to 75 percent of typical costs established at the county level, with rates of up to 90 percent for beginning, resource-limited, and socially disadvantaged farmers. Annual payments are also offered for the adoption of conservation-compatible management practices, including irrigation water management. In 2008, EQIP accounted for 58 and 54 percent of farms reporting public financial assistance for irrigation investments across Western and Eastern States, respectively (table 6).³⁵ Other USDA financial assistance programs (e.g., Conservation Stewardship Program, Wetlands Reserve Program) accounted for 25 percent of farms reporting assistance, with the remaining funding provided by non-USDA programs (e.g., U.S. Environmental Protection Agency, Bureau of Reclamation, as well as State and local water management and supply district programs).

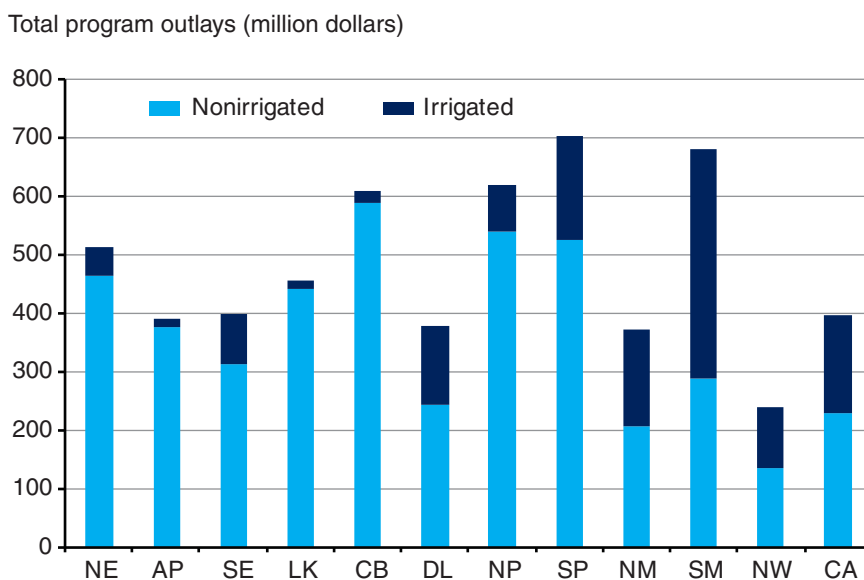
Figure 15 shows EQIP expenditures for irrigation practices as a share of total program outlays, by region, for 2004-10.³⁶ Nationally, irrigation practices accounted for \$1.4 billion in program expenditures over this period (USDA/NRCS, 2004-10), or roughly a quarter of total EQIP financial assistance. The magnitude of public irrigation investment under EQIP varied across the United States, partly reflecting the relative importance of irrigation to the agricultural economy.³⁷ In Western States, EQIP funding of irrigation practices (as a share of total program outlays) ranged from 13.0 percent in the Northern Plains to 57.7 percent in Southern Mountain States. Irrigation

³⁵Farms reporting EQIP funding assistance represented 4 percent of all U.S. irrigated farms making irrigation investments in 2008. The statistics here represent only a snapshot of EQIP participants for the 2008 production year and do not reflect program participation over time.

³⁶Funding levels reported here represent fiscal year dollars obligated.

³⁷The conservation of ground and surface water resources is one of several priority resource concerns used to set State funding allocations and to rank local contract offers under EQIP.

Figure 15
Environmental Quality Incentives Program funding for irrigation practices, by region, 2004-10



NE=Northeast; AP=Appalachia; SE=Southeast; LK=Lake States; CB=Cornbelt; DL=Delta; NP=Northern Plains; SP=Southern Plains; NM=Northern Mountain; SM=Southern Mountain; NW=Northwest; CA=California.

Source: USDA, Economic Research Service calculations based on USDA's Natural Resource Conservation Service, Environmental Quality Incentives Program data, 2004-10.

practices accounted for a relatively small share of program expenditures in the Corn Belt, Lake States, Appalachian, and Northeast regions. Since 2004, however, the shares of EQIP funding for irrigation practices generally have increased in Eastern States while they have declined across the West.

A wide range of irrigation-related practices are eligible for financial assistance under EQIP. More than half (55.8 percent) of EQIP irrigation funding was devoted to upgrades in onfarm water application systems (USDA/NRCS, 2004-10). Approximately 34.7 percent of funding was allocated to improved onfarm water conveyance. Water supply practices represented a relatively small portion (9.4 percent) of total irrigation expenditures under EQIP, reflecting program emphasis on enhancing producer adoption of improved onfarm irrigation practices for existing irrigation. In a recent report, USDA's NRCS estimated that, as of 2007, the EQIP program treated about 4.0 million irrigated acres and, by the end of 2012, EQIP is expected to treat an additional 2.0 million irrigated acres with water-conserving irrigation practices (USDA/NRCS, 2010). The study estimated benefits for irrigation conservation funding at \$10.30 per acre. This measure is considered conservative because not all benefits could be taken into account.³⁸

³⁸The NRCS evaluation of EQIP funding for irrigation conservation, conducted consistent with Office of Management and Budget guidelines as part of an official rule-making process, did not include benefits for productivity changes, input-cost savings, water quality and environmental impacts, or a measure of the nonagricultural market value of saved water. The study also assumed that water saved on the farm would be available for other agricultural activities, other competing uses (municipal, power, or fish habitat), or sold locally via irrigation rental markets, but did not account for these adjustments within the benefit/cost analysis (USDA/NRCS, 2010).

Summary and Policy Implications

Irrigated agriculture makes a significant contribution to the value of U.S. agricultural production. Based on 2007 Census of Agriculture data, irrigated farms accounted for \$118.5 billion in sales, or roughly 40 percent of the value of U.S. agricultural production, with the national average value of production for irrigated farms 3.3 times the average value for nonirrigated farms (farms not irrigating any land). Irrigated farms accounted for 54.5 percent (\$78.3 billion) of the value of all crop products sold, while also contributing significantly to the value of livestock and poultry production through animal forage and feed production.

In 2007, nearly 57 million U.S. acres were irrigated, representing 7.5 percent of all cropland and pastureland. The 12 leading irrigation States accounted for 77.2 percent of all irrigated acres, with Nebraska, California, and Texas leading all other States with 8.6, 8.0, and 5.0 million irrigated acres, respectively. Two States among the 31 Eastern States—Arkansas and Florida—were among the 12 leading irrigation States, with 4.5 and 1.6 million acres, respectively. Nearly three-quarters of U.S. irrigated agriculture occurred in the 17 Western States, including 73 percent of harvested irrigated cropland and 94 percent of irrigated pastureland. Farm and Ranch Irrigation Survey data for 2008 indicated that U.S. irrigated agriculture used nearly 91 maf of water. Irrigators across the Western States applied nearly 74.2 maf of water for irrigated cropland production, with 52.4 percent originating from surface-water sources and the remaining 47.7 percent pumped from wells drawing water from regional and local aquifers.

Population and economic growth, changing social values with respect to water quality and the environment, and Native American water-right claims have been and will continue to be forces driving demand for water resources within the United States. Resolving Native American water-right claims, once estimated at nearly 46 maf annually, could have a significant impact on future surface/groundwater supplies for agriculture. As more States move beyond the minimum instream-flow concept to formally recognize environmental flows—instream flows required to maintain sustainable fish and wildlife habitats or to re-establish natural habitats—the volume of water reallocated from agriculture to meet environmental needs likely will increase. More recently, emerging demands for water resources have heightened water scarcity concerns, particularly across the Western States. Biofuel development, whether through corn-based ethanol or cellulosic feedstock sources, may increase demand for water resources in some regions. Over time, climate change impacts are expected to alter both water supplies and water demands across and within regions. Warming temperatures, changing precipitation patterns, and reduced snowpack are expected to significantly reduce late spring/summer streamflows (flows that historically were available for reservoir storage to meet peak irrigation water demands) and groundwater recharge across much of the West. In addition, higher temperatures are expected to increase crop-water demands via reduced crop ET efficiency.

Competing demands for U.S. water resources will continue to grow, while the potential for new, large-scale water-supply projects is fairly limited. Agriculture accounts for more than 80 percent of U.S. consumptive water use

and, with the lowest marginal value of water among competing out-of-stream uses, will be the likely water source to meet future water demands. Emerging demands already are placing new pressures on existing water allocations, particularly across the West, heightening the importance of water conservation for irrigated agriculture sustainability. The future sustainability of the irrigated agriculture sector will depend a great deal on a variety of factors, such as water-use efficiency, conservation policies that encourage more efficient onfarm water management, and how and when increasingly scarce water supplies are reallocated among competing demands.

Since the 1970s, data reveal a substantial and sustained shift across the Western States from traditional gravity-fed and flood irrigation to more efficient gravity and pressure/sprinkler irrigation systems. In 2008, about \$2.15 billion was invested in U.S. irrigation systems, with the majority (\$1.6 billion) invested in Western States. Most irrigation investment was financed privately, with less than 10 percent of farms reporting irrigation improvements in 2008 using public financial assistance for irrigation upgrades. The data indicate that, while substantial technological innovation has already occurred in U.S. irrigated agriculture, significant room for improvement exists. At least half of irrigated cropland acreage across both Western and Eastern States is still irrigated with traditional (less efficient) irrigation application systems. In addition, survey data indicate that most irrigators do not implement more efficient onfarm water management practices. Fewer than 10 percent used soil- or plant-moisture sensing devices or commercial irrigation scheduling services. Less than 2 percent of irrigators used computer-based simulation models to evaluate crop irrigation requirements based on consumptive-use needs and local weather conditions.

Adoption of more efficient irrigation application systems has been and will be an important component of agricultural water conservation efforts. During 2004-10, most of USDA's EQIP irrigation funding was devoted to upgrades in onfarm water application and onfarm water conveyance systems. The sustainability of irrigated agriculture, however, could be enhanced further if producers combined improved onfarm water management practices with high-efficiency irrigation application systems. In addition, through collaborative Federal, State, and local partnerships under USDA's Agricultural Water Enhancement Program, integration of onfarm conservation efforts with watershed-level water management tools could further encourage increased conservation of water resources for current, alternative, and future uses. Integrating irrigation efficiency improvements with other practices, such as deficit irrigation, acreage idling, and off-farm water transfers that compensate agricultural producers for water conservation gains, may allow producers to balance the drop in yields that often accompanies efforts to reduce irrigation water use with potentially improved profitability through reduced costs of applying water and related inputs and increased water-related revenue. Integrating onfarm conservation and Federal/State institutional mechanisms also may encourage producers and other stakeholders to interact jointly in determining market-based water reallocations.

Designing agricultural water conservation policies that promote a more sustainable future for irrigated agriculture depends a great deal on improving the economic analysis of adaptation options within the irrigated farm sector. While previous economic studies of agricultural water-conservation issues

have been helpful, these studies were limited in their ability to handle the broad range of “production system” adaptation strategies that will help irrigated agriculture adjust to a future of increasing competition for a stable or declining supply of water. This reduced-supply, rising-demand environment will place increased pressures on producers to adopt production systems that simultaneously reduce crop consumptive water use while maintaining farm profits. Managing water on the farm, whether applied by gravity or by high- or low-pressure sprinkler irrigation, will become an increasingly important part of the farm’s irrigation production system technology.

In an increasingly water-scarce world, production system adaptation strategies are likely to involve complex production decisions on crop choice, water application rates, and adopting efficient irrigation technology and water management practices that adjust to changing water-supply conditions over time. Economic analyses from a production system perspective could simultaneously consider all the components of a producer’s production decisions—crop choice, crop yield target, irrigation system type, and onfarm water management regime—combined with field-level physical/environmental characteristics and water-supply conditions. As competing demands and climate change increasingly strain the water supply/demand environment for agriculture, economic analysis of water conservation policy issues and their impact on agricultural production and regional resource use and quality will become more complex. Such analyses, however, could also enhance the quality and reliability of information on irrigation choices, improving our understanding of irrigated agriculture’s adaptability toward a more sustainable future.

References

- Aillery, Marcel, Robbin Shoemaker, and Margriet Caswell. "Agriculture and Ecosystem Restoration in South Florida: Assessing Trade-Offs from Water-Retention Development in the Everglades Agricultural Area," *American Journal of Agricultural Economics* Vol. 83, No. 1: pp. 183-95, February 2001.
- Ayars, James E. "Adapting Irrigated Agriculture to Drought in the San Joaquin Valley of California," *Policy Note 03-0910*, University of California-Riverside, Water Science and Policy Center, p. 4, September 2010, http://wspc.ucr.edu/policy_notes/PN_03_0910_Drought.pdf.
- Bartis, J.T., T. LaTourrette, L. Dixon, D.J. Peterson, and G. Cecchine. *Oil Shale Development in the United States: Prospects and Policy Issues*, RAND Corporation: Arlington, VA, p. 68, 2005.
- Bates, B.C., Z.W. Kundzewicz, S. Wu, and J.P. Palutikof (Eds.). *Climate Change and Water*, IPCC Technical Paper VI, Intergovernmental Panel on Climate Change, IPCC Secretariat: Geneva, p. 210, 2008.
- Bernhardt, E.S., M.A. Palmer, J.D. Allan, G. Alexander, K. Barnas, S. Brooks, J. Carr, S. Clayton, C. Dahm, J. Follstad-Shah, D. Galat, S. Gloss, P. Goodwin, D. Hart, B. Hassett, R. Jenkinson, S. Katz, G.M. Kondolf, P.S. Lake, R. Lave, J.L. Meyer, T.K. O'Donnell, L. Pagano, B. Powell, and E. Sudduth. "Synthesizing U.S. River Restoration Efforts," *Science* Vol. 308, No. 5722: pp. 636-37, April 2005.
- Brekke, L.D., J.E. Kiang, J.R. Olsen, R.S. Pulwarty, D.A. Raff, D.P. Turnipseed, R.S. Webb, and K.D. White. *Climate Change and Water Resources Management—A Federal Perspective*, U.S. Geological Survey, Circular 1331, p. 65, 2009.
- Burt, C.M., A.J. Clemmens, T.S. Strelkoff, K.H. Solomon, R.D. Bliesner, L.A. Hardy, T.A. Howell, and D.E. Eisenhauer. "Irrigation Performance Measures: Efficiency and Uniformity," *Journal of Irrigation and Drainage Engineering* Vol. 123 (6): pp. 423-42, November 1997.
- CALFED Bay-Delta Program. CALFED Record of Decision, 2010, http://calwater.ca.gov/calfed/objectives/ecosystem_restoration.html.
- California Department of Conservation. *2006-2008 California Farmland Conversion Report*, Farmland Division of Land Resource Protection, Mapping and Monitoring Program: Sacramento, CA, p. 97, 2011.
- Carey, Janis M., and David Zilberman. "A Model of Investment Under Uncertainty: Modern Irrigation Technology and Emerging Markets in Water," *American Journal of Agricultural Economics* Vol. 84, No. 1: pp. 171-83, February 2002.
- Caswell, M., and D. Zilberman. "The Choices of Irrigation Technologies in California," *American Journal of Agricultural Economics* Vol. 67: pp. 224-34, May 1985.

- Center for Irrigation Technology (CIT). *Agricultural Water Use in California: A 2011 Update*, Staff Report, California State University, p. 79, November 2011.
- Chesapeake Energy. “Water Use in Deep Shale Gas Exploration,” *Fact Sheet*, p. 2, May 2011, <http://www.chk.com/Media/Educational-Library/Fact-Sheets/Pages/default.aspx>.
- Chiu, Yi-Wen, B. Walseth, and S. Suh. “Water Embodied in Bio-Ethanol in the United States,” *Environmental Science and Technology* Vol. 43, No. 8: pp. 2688-92, 2009.
- Christensen, N.S., and D.P. Lettenmaier. “A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin,” *Hydrology and Earth System Sciences* Vol. 11: pp. 1417-34, 2007.
- Claims Resolution Act of 2010. Titles III – VI, Public Law 111-291, pp. 3073-3156, December 8, 2010.
- Clemmens, A.J., R.G. Allen, and C.M. Burt. “Technical Concepts Related to Conservation of Irrigation and Rainwater in Agricultural Systems,” *Water Resources Research* Vol. 44, W00E03, doi:10.1029/2007WR006095, p. 16, 2008.
- Circlepoint. *Listen to the River: An Independent Review of the CVPIA Fisheries Program*, U.S. Bureau of Reclamation and the U.S. Fish and Wildlife Service, p. 51, December 2008.
- Congressional Budget Office (CBO). *Water Use Conflicts in the West: Implications of Reforming the Bureau of Reclamation’s Water Supply Policies*, United States Congress, August 1997.
- Department of Water Resources (DWR). *DWR Increases Water Allocation: Final Delivery Estimate is 45 Percent of Requests*, DWR News Releases, California, May 20, 2010a, <http://www.water.ca.gov/news/newsreleases/2010/05202010finalallocation.pdf>.
- Department of Water Resources (DWR). *Late Spring Weather Allows DWR to Increase Water Allocation: Final Delivery Estimate is 50 Percent of Requests*, DWR News Releases, California, June 23, 2010b, <http://www.water.ca.gov/news/newsreleases/2010/06232010revisedfinalallocation.pdf>.
- Dettinger, Michael, and Sam Earman. “Western Groundwater and Climate Change—Pivotal to Supply Sustainability or Vulnerability in its Own Right?” *Ground Water: News and Views* Vol. 4, No. 1: pp. 4-5, June 2007.
- Evans, Robert G., and E. John Sadler. “Methods and technologies to improve efficiency of water use,” *Water Resources Research* Vol. 44, W00E04, doi:10.1029/2007WR006200, p. 15, 2008.

- Evelt, Steven, Dennis Carman, and Dale Bucks. "Expansion of Irrigation in the Mid South United States: Water Allocation and Research Issues," *Proceedings, 2nd International Conference on Irrigation and Drainage, Water for a Sustainable World—Limited Supplies and Expanding Demand*, U.S. Committee on Irrigation and Drainage: Phoenix, AZ, pp. 247-60, May 12-15, 2003.
- Fereres, Elias, and María Auxiliadora Soriano. "Deficit irrigation for reducing agricultural water use," *Journal of Experimental Botany*, Special Issue, Vol. 58, No. 2: pp. 147-59, 2007.
- Fischer Farm Services. *Reasons to Invest in Mississippi Farmland*, Aberdeen, MS, 2011, http://www.fischerfarmservices.com/reasons_farm.html.
- Florida Department of Environmental Protection (DEP). *Sustaining Our Water Resources: Annual Report on Regional Water Supply Planning*, p. 21, March 2010.
- Gardner, B. Delworth, and Herbert H. Fullerton. "Transfer Restrictions and Misallocations of Irrigation Water," *American Journal of Agricultural Economics* Vol. 50, No. 3: pp. 556-71, 1968.
- Geerts, Sam, and Dirk Raes. "Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas," *Agricultural Water Management* Vol. 96, No. 9: pp. 1275-84, 2009.
- Gillon, K., M. Cohen, J. Pitt, J. Wechsler, G. Voggesser, P. Culp, F. Zamora, R. Wigington, and P. Hyde. *Conservation Before Shortage II: Proposal for Colorado River Operations*, Defenders of Wildlife, Environmental Defense, National Wildlife Federation, The Nature Conservancy, Pacific Institute, Sierra Club, Sonoran Institute, pp. 1-9, July 2006, http://www.pacinst.org/topics/water_and_sustainability/colorado_river/shortage_proposal/CBS_II.pdf.
- Gollehon, N., and W. Quinby. "Irrigation Resources and Water Costs," *Agricultural Resources and Environmental Indicators, 2006 Edition*, EIB-16, U.S. Department of Agriculture, Economic Research Service, pp. 24-32, 2006.
- Green, Timothy R., Makoto Taniguchi, and Henk Kooi. "Potential Impacts of Climate Change and Human Activity on Subsurface Water Resources," *Vadose Zone Journal* Vol. 6, No. 3: pp. 531-32, August 2007.
- Gregory, Liana. "Technically Open: The Debate Over Native American Reserved Groundwater Rights," *Journal of Land, Resources, and Environmental Law* Vol. 28, No. 2: pp. 361-73, 2008.
- Ground Water Protection Council (GWPC) and All Consulting. *Modern Shale Gas Development in the United States: A Primer*, U.S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, Contract DE-FG26-04NT15455, p. 96, April 2009.

- Hall, Noah D., Bret B. Stuntz, and Robert H. Abrams. "Climate Change and Freshwater Resources," *Natural Resources & Environment* Vol. 22, No. 3 (Winter): pp. 30-5, 2008.
- Hamilton, J.R., N.K. Whittlesey, and P. Halverson. "Interruptible Water Markets in the Pacific Northwest," *American Journal of Agricultural Economics* Vol. 71, No. 1: pp. 63-75, February 1989.
- Harwood, J., R. Heifner, K. Coble, J. Perry, and A. Somwaru. *Managing Risk in Farming: Concepts, Research, and Analysis*, AER-774, U.S. Department of Agriculture, Economic Research Service, p. 125, March 1999.
- Hatfield, J.L., K.J. Boote, P.A. Fay, G.L. Hahn, R.C. Izaurralde, B.A. Kimball, T.L. Mader, J.A. Morgan, D.R. Ort, H.W. Polley, A.M. Thomson, and D.W. Wolfe. "Agriculture," *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States*, U.S. Climate Change Science Program and the Subcommittee on Global Change Research: Washington, DC, p. 21-74, May 2008.
- Hoerling, M., and J. Eischeid. "Past Peak Water in the Southwest," *Southwest Hydrology* Vol. 6, p. 18, 2007.
- Hornbaker, R.H., and H.P. Mapp. "A Dynamic Analysis of Water Savings from Advanced Irrigation Technology," *Western Journal of Agricultural Economics* Vol. 13, No. 2: pp. 307-15, 1988.
- Howe, C.W. "Economic, Legal, and Hydrologic Dimensions of Potential Interstate Water Markets," *American Journal of Agricultural Economics* Vol. 67, No. 5: pp. 1226-30, 1985.
- Howell, T.A. "Irrigation Efficiency," *Encyclopedia of Water Science*, pp. 467-72, 2003.
- Huffaker, R. "Impacts of Biofuels on Water Supply: Proposed Cures May Worsen the Disease," *Choices* Vol. 25, No. 3, 3rd Quarter: pp. 7-10, 2010.
- Huffaker, R., and N. Whittlesey. "A Theoretical Analysis of Economic Incentive Policies Encouraging Agricultural Water Conservation," *Water Resources Development* Vol. 19, No. 1: pp. 37-53, 2003.
- Intergovernmental Panel on Climate Change (IPCC Report). "Climate Change 2007: Impacts, Adaptation and Vulnerability," *Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, J.P. van der Linden, and C.E. Hanson (Eds.), Cambridge University Press: Cambridge, UK, p. 976, 2007.

- Izaurre, R.C., N.J. Rosenberg, R.A. Brown, and A.M. Thomson. "Integrated assessment of Hadley Center (HadCM2) climate-change impacts on agricultural productivity and irrigation water supply in the conterminous United States, Part II: Regional agricultural production in 2030 and 2095," *Agricultural and Forest Meteorology* Vol. 117, pp. 97-122, 2003.
- Jerla, Carly, and Jim Prairie. "Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead & Efforts Addressing Climate Change and Variability," *Intermountain West Climate Summary* Vol. 5, Issue 1: pp. 5-7, January 2009.
- Kenny, J.F., N.L. Barber, S.S. Hutson, K.S. Linsey, J.K. Lovelace, and M.A. Maupin. *Estimated Use of Water in the United States in 2005*, Circular 1344, U.S. Department of the Interior, U.S. Geological Survey, p. 52, 2009.
- Kim, C.S., G.D. Schaible, and S.G. Daberkow. "An Efficient Cost-Sharing Program to Reduce Nonpoint-Source Contamination: Theory and an Application to Groundwater Contamination," *Environmental Geology* Vol. 39, No. 6: pp. 649-59, April 2000.
- Kim, C.S., M.R. Moore, J. Hanchar, and M. Nieswiadomy. "A Dynamic Model of Adaptation to Resource Depletion: Theory and an Application to Groundwater Mining," *Journal of Environmental Economics and Management* Vol. 17, No. 1: pp. 66-82, 1989.
- Knowles, Noah, Michael D. Dettinger, and Daniel R. Cyan. "Trends in Snowfall versus Rainfall in the Western United States," *Journal of Climate* Vol. 19, Issue 18: pp. 4545-59, September 2006.
- Landry, C. "Market transfers of water for environmental protection in the western United States," *Water Policy* Vol. 1, No. 5: pp. 457-69, 1998.
- Lemke, P., J. Ren, R. Alley, I. Allison, J. Carrasco, G. Flato, Y. Fujii, G. Kaser, P. Mote, R.H. Thomas, and T. Zhang. "Observations: Changes in Snow, Ice and Frozen Ground," *Climate Change 2007: The Physical Science Basis, a Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Quin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (Eds.), Cambridge University Press: Cambridge and New York, pp. 337-84, 2007.
- MacDonnell, Lawrence J. "Environmental Flows in the Rocky Mountain West: A Progress Report," *Wyoming Law Review* Vol. 9, No. 2: pp. 335-96, 2009.
- Malcolm, Scott A., Marcel Aillery, and Marca Weinberg. *Ethanol and a Changing Agricultural Landscape*, ERR-86, U.S. Department of Agriculture, Economic Research Service, p. 58, November 2009.

- Martin, W.E. "Evolving Water Institutions in an Urbanizing West: Discussion," *American Journal of Agricultural Economics* Vol. 68: pp. 1152-54, 1986.
- McCabe, G.J., and D.M. Wolock. "Warming may create substantial water supply shortages in the Colorado River basin," *Geophysical Research Letters* Vol. 34, L22708: pp. 1-5, November 2007.
- Midwest Irrigation. *Midwest States Increase Irrigation*, The Net Irrigate Blog, 2010, <http://netirrigate.wordpress.com/tag/midwest-irrigation/>.
- Moore, M.R. "Native American Water Rights: Efficiency and Fairness," *Natural Resources Journal* Vol. 29 (Summer): pp. 763-91, 1989.
- Moore, M.R. "The Bureau of Reclamation's New Mandate for Irrigation Water Conservation: Purposes and Policy Alternatives," *Water Resources Research* Vol. 27: pp. 145-55, February 1991.
- Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier. "Declining Mountain Snowpack in Western North America," *Bulletin of the American Meteorological Society* Vol. 86: pp. 39-49, 2005.
- Mote, P.W., E.A. Parson, A.F. Hamlet, W.S. Keeton, D. Lettenmaier, N. Mantau, E.L. Miles, D.W. Peterson, D.L. Peterson, R. Slaughter, and A.K. Snover. "Preparing for Climate Change: The Water, Salmon, and Forests of the Pacific Northwest," *Climate Change* Vol. 61: pp. 45-88, 2003.
- National Energy Technology Laboratory (NETL). *Estimating Freshwater Needs to Meet Future Thermolectric Generation Requirements, 2008 Update*, DOE/NETL-400/2008/1339, p. 107, September 2008, http://www.netl.doe.gov/technologies/coalpower/ewr/pubs/2008_Water_Needs_Analysis-Final_10-2-2008.pdf.
- National Research Council (NRC). *A New Era for Irrigation*, Water Science and Technology Board, National Academies Press: Washington, DC, 1996.
- National Research Council (NRC). *Toward Sustainable Agricultural Systems in the 21st Century*, Board on Agriculture and Natural Resources, National Academies Press: Washington, DC, 2010.
- National Research Council (NRC). *Water Implications of Biofuels Production in the United States*, Water Science and Technology Board, National Academies Press: Washington, DC, p. 86, 2008.
- National Water Assessment Group (NWAG Report). *Water: The Potential Consequences of Climate Variability and Change*, Peter Gleick (project lead), U.S. Global Change Research Program: Oakland, CA, p. 160, September 2000.
- Negri, D.H., and D.H. Brooks. "Determinants of Irrigation Technology Choice," *Western Journal of Agricultural Economics* Vol. 15, No. 2: pp. 213-23, December 1990.

- Peterson, J.M., T.L. Marsh, and J.R. Williams. "Conserving the Ogallala Aquifer: Efficiency, Equity, and Moral Motives," *Choices*, First Quarter, pp. 15-8, 2003.
- Poff, N.L., J.D. Allan, M.A. Palmer, D.D. Hart, B.D. Richter, A.H. Arthington, K.H. Rogers, J.L. Meyer, and J.A. Stanford. "River Flows and Water Wars: Emerging Science for Environmental Decision Making," *Frontiers in Ecology and the Environment* Vol. 1, Issue 6: pp. 298-306, August 2003.
- Rood, S.B., G.M. Samuelson, J.K. Weber, and K.A. Wyrot. "Twentieth-century decline in streamflows from the hydrographic apex of North America," *Journal of Hydrology* Vol. 306: pp. 215-33, 2005.
- Sadler, E.J., R.G. Evans, K.C. Stone, and C.R. Camp. "Opportunities for Conservation with Precision Irrigation," *Journal of Soil and Water Conservation* Vol. 60, No. 6: pp. 371-79, 2005.
- Schaible, G.D. "Economic and Conservation Tradeoffs of Regulatory vs. Incentive-based Water Policy in the Pacific Northwest," *International Journal of Water Resources Development* Vol. 16, No. 2: pp. 221-38, 2000.
- Schaible, G.D. "Water Conservation Policy Analysis: An Interregional, Multi-Output, Primal-Dual Optimization Approach," *American Journal of Agricultural Economics* Vol. 79: pp. 163-77, February 1997.
- Schaible, G.D. *Western Irrigated Agriculture*, data set, U.S. Department of Agriculture, Economic Research Service, 2004, <http://www.ers.usda.gov/Data/WesternIrrigation>.
- Schaible, G.D., C.S. Kim, and M.P. Aillery. "Dynamic Adjustment of Irrigation Technology/Water Management in Western U.S. Agriculture: Toward a Sustainable Future," *Canadian Journal of Agricultural Economics* Vol. 58: pp. 433-61, December 2010.
- Schaible, G.D., and M.P. Aillery. "Irrigation Technology Transitions in the Mid-Plains States: Implications for Water Conservation/Water Quality Goals and Institutional Changes," *Water Resources Development* Vol. 19, No. 1: pp. 67-88, 2003.
- Schaible, G.D., and M.P. Aillery. "Irrigation Water Management," *Agricultural Resources and Environmental Indicators: 2006 Edition*, EIB-16, U.S. Department of Agriculture, Economic Research Service, pp. 134-43, 2006, http://www.ers.usda.gov/publications/arei/eib16/eib16_4-6.pdf.
- Schuck, E.C., W.M. Frasier, R.S. Webb, L.J. Ellingson, and W.J. Umberger. "Adoption of More Technically Efficient Irrigation Systems as a Drought Response," *International Journal of Water Resources Development* Vol. 21, No. 4: pp. 651-62, 2005.

- Seaber, Paul R., F. Paul Kapinos, and George L. Knapp. *Hydrologic Unit Maps*, Water-Supply Paper 2294, U.S. Department of the Interior, U.S. Geological Survey, p. 20, 1987, http://pubs.usgs.gov/wsp/wsp2294/pdf/wsp_2294_a.pdf.
- Soil and Water Conservation Service (SWCS) and Environmental Defense (ED). *Environmental Quality Incentives Program (EQIP): Program Assessment*, p. 34, March 2007, http://www.swcs.org/documents/filelibrary/EQIP_assessment.pdf.
- Sophocleous, Marios. "The Science and Practice of Environmental Flows and the Role of Hydrogeologists," *Ground Water* Vol. 45, No. 4: pp. 393-401, July-August 2007.
- Supalla, Raymond J. Personal communication, University of Nebraska-Lincoln, Agricultural Economics Department, 2011.
- U.S. Climate Change Science Program (U.S. CCSP), and the Subcommittee on Global Change Research. *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States*, P. Backlund, A. Janetos, D. Schimel, J. Hatfield, K. Boote, P. Fay, L. Hahn, C. Izaurralde, B.A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thomson, D. Wolfe, M.G. Ryan, S.R. Archer, R. Birdsey, C. Dahm, L. Heath, J. Hicke, D. Hollinger, T. Huxman, G. Okin, R. Oren, J. Randerson, W. Schlesinger, D. Lettenmaier, D. Major, L. Poff, S. Running, L. Hansen, D. Inouye, B.P. Kelly, L. Meyerson, B. Peterson, and R. Shaw (Contrib.), U.S. Department of Agriculture, p. 362, 2008.
- U.S. Department of Agriculture, National Agricultural Statistics Service (USDA/NASS). *2007 Census of Agriculture: U.S. Summary and State Data*, Vol. 1, Geographic Area Series, Part 51 (AC-07-A-51), p. 739, 2009, http://www.agcensus.usda.gov/Publications/2007/Full_Report/usv1.pdf.
- U.S. Department of Agriculture, National Agricultural Statistics Service (USDA/NASS). *Farm and Ranch Irrigation Survey (2008)*, Vol. 3, Special Studies of the 2007 Census of Agriculture, Part I (AC-07-SS-1), p. 268, February 2010, http://www.agcensus.usda.gov/Publications/2007/Online_Highlights/Farm_and_Ranch_Irrigation_Survey/index.asp.
- U.S. Department of Agriculture, National Agricultural Statistics Service (USDA/NASS), and Economic Research Service. *Farm and Ranch Irrigation Survey, 1984-2008*.
- U.S. Department of Agriculture, Natural Resources Conservation Service (USDA/NRCS). "Conservation Practices that Save: Irrigation Water Management," *Save Energy Save Money*, 2006, http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_023630.pdf.
- U.S. Department of Agriculture, Natural Resources Conservation Service (USDA/NRCS). Environmental Quality Incentives Program (EQIP) contract data from the NRCS PROTRACTS database, 2004-10.

- U.S. Department of Agriculture, Natural Resources Conservation Service (USDA/NRCS). *Final Benefit-Cost Analysis for the Environmental Quality Incentives Program (EQIP)*, p. 116, May 2010, http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs143_007977.pdf.
- U.S. Department of Agriculture, Research, Education, and Economics (USDA/REE). *Agricultural Water Security Listening Session—Final Report*, J.P. Dobrowolski and M.P. O’Neill (Eds.), p. 31, 2004.
- U.S. Department of Agriculture, Research, Education, and Economics (USDA/REE). *Research, Education, and Economics Action Plan*, Office of the Under Secretary for Research, Education, and Economics, p. 37, February 2012.
- U.S. Department of Agriculture (USDA), Office of the Secretary. Strategic Plan FY 2010 – 2015, p. 50, 2012, http://www.usda.gov/wps/portal/usda/usdahome?navid=ABOUT_USDA.
- U.S. Department of Energy (U.S. DOE). “Concentrating Solar Power Commercial Application Study: Reducing Water Consumption of Concentrating Solar Power Electricity Generation,” *A Report to Congress*, p. 35, 2010, http://www1.eere.energy.gov/solar/pdfs/csp_Water_Study.pdf.
- U.S. Department of the Interior, Bureau of Land Management (U.S. BLM). *Oil Shale Fact Sheet*, 2011, http://www.blm.gov/pgdata/etc/medialib/blm/wo/Communications_Directorate/public_affairs/news_release_attachments.Par.96261.File.tmp/OilShaleFS_022011.pdf.
- U.S. Department of the Interior, Bureau of Reclamation (U.S. BoR). *Bay Delta Conservation Plan: Status Update 3*, June 2010, http://www.assembly.ca.gov/acs/committee/c26/hearings/111910/BDCP_Status_Update_3_June_2010.pdf.
- U.S. Department of the Interior, Bureau of Reclamation (U.S. BoR). *Central Valley Project Improvement Act Program Activity Review Report*, August 25, 2009, http://www.usbr.gov/mp/cvpia/docs_reports/docs/2009_Final%20CPAR%20Report%208-25-09.pdf.
- U.S. Department of the Interior, Bureau of Reclamation (U.S. BoR). *Final EIS – Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations for Lake Powell and Lake Mead*, October 2007.
- U.S. Department of the Interior, Bureau of Reclamation (U.S. BoR). *Interior’s Indian Water Rights Settlement Program – Reclamation Support for Secretary’s Program*, June 12, 2012, <http://www.usbr.gov/native/waterrights/waterrights.html>.

- U.S. Department of the Interior, Bureau of Reclamation (U.S. BoR). *Secure Water Act Section 9503(c)—Reclamation Climate Change and Water, Report to Congress*, Patty Alexander, Brekke Levi, Gray Davis, Subhrendu Gangopadhyay, Katrina Grantz, Charles Hennig, Carly Jerla, Dagmar Llewellyn, Paul Miller, Tom Pruitt, David Raff, Tom Scott, Michael Tansey, and Toni Turner (Contrib.), Denver, CO, p. 205, April 2011, <http://www.usbr.gov/climate/SECURE/docs/SECUREWaterReport.pdf>.
- U.S. Department of the Interior, U.S. Geological Survey (USGS). *Effects of Climate Variability and Change on Groundwater Resources of the United States*, Fact Sheet 2009-3074, J.J. Gurdak, R.T. Hanson, and T.R. Green(Contrib.), p. 4, September 2009.
- U.S. Department of the Interior, U.S. Geological Survey (USGS). *Groundwater Atlas of the United States*, Alabama, Florida, Georgia, and South Carolina (HA 730-G), http://pubs.usgs.gov/ha/ha730/ch_g/G-text1.html; Iowa, Michigan, Minnesota, and Wisconsin (HA 730-J), http://pubs.usgs.gov/ha/ha730/ch_j/J-text1.html; and Arkansas, Louisiana, and Mississippi (HA 730-F), http://pubs.usgs.gov/ha/ha730/ch_f/F-text1.html, 2011.
- U.S. Department of the Interior, U.S. Geological Survey (USGS). National Water-Quality Assessment (NAWQA) studies, 2011, <http://water.usgs.gov/nawqa/bib>.
- U.S. Department of the Interior, U.S. Geological Survey (USGS). *Water Use in Florida, 2005 and Trends 1950-2005*, Fact Sheet 2008-3080, Richard L. Marella (Ed.), p. 7, September 2008.
- U.S. Government Accountability Office (U.S. GAO). *Energy-Water Nexus: A Better and Coordinated Understanding of Water Resources Could Help Mitigate the Impacts of Potential Oil Shale Development*, GAO-11-35, p. 69, October 2010.
- U.S. Government Accountability Office (U.S. GAO). *Energy-Water Nexus: Many Uncertainties Remain about National and Regional Effects of Increased Biofuel Production on Water Resources*, GAO-10-116, U.S. House of Representatives, Committee on Science and Technology, p. 50, 2009.
- U.S. Senate Committee on Indian Affairs. *Oversight Hearing on Indian Water Rights: Promoting the Negotiation and Implementation of Water Settlements in Indian Country*, webcast, March 15, 2012, <http://www.indian.senate.gov/hearings/hearing.cfm?hearingID=eb997a7c3376c76b36a041cf2a0ba6c1>.
- Van Kirk, R.W., and S.W. Naman. "Relative Effects of Climate and Water Use on Base-Flow Trends in the Lower Klamath Basin," *Journal of American Water Resources Association* Vol. 44, No. 4: pp. 1035-52, August 2008.

- Vories, Earl D., and Steven R. Evett. "Irrigation Research Needs in the USA Mid-South and Southeast, Humid and Subhumid Regions," *Proceedings for the 5th National Decennial Irrigation Conference*, ASABE # IRR10-8679, American Society of Agricultural and Biological Engineers (ASABE) and the Irrigation Association: Phoenix, AZ, M. Dukes (Ed.), pp. 1-12, December 5-8, 2010.
- Wall, Ellen, and Barry Smit. "Climate Change Adaptation in Light of Sustainable Agriculture," *Journal of Sustainable Agriculture* Vol. 27, No. 1: pp. 113-23, 2005.
- Wallander, Steven, Roger Claassen, and Cynthia Nickerson. *The Ethanol Decade: An Expansion of U.S. Corn Production, 2000-09*, EIB-79, U.S. Department of Agriculture, Economic Research Service, p. 16, August 2011.
- Ward, F.A., and M. Pulido-Velazquez. "Water conservation in irrigation can increase water use," *Proceedings of the National Academy of Sciences* Vol. 105, No. 47: pp. 18218-20, 2008.
- Weinberg, M., C.L. Kling, and J.E. Wilen. "Water Markets and Water Quality," *American Journal of Agricultural Economics* Vol. 75, No. 2: pp. 278-91, May 1993.
- Western States Water Council. *Indian Water Rights in the West*, Western Governors Association, May 1984.
- Whittlesey, N.K., and R.G. Huffaker. "Water Policy Issues for the Twenty-first Century," *American Journal of Agricultural Economics* Vol. 77: pp. 1199-203, December 1995.
- Zellmer, Sandra. "Legal Tools for Instream Flow Protection," *Integrated Approaches to Riverine Resource Stewardship: Case Studies, Science, Law, People, and Policy*, A. Locke, C. Stalnaker, S. Zellmer, K. Williams, H. Beecher, T. Richards, C. Robertson, A. Wald, A. Paul, and T. Annear (Contrib.), The Instream Flow Council: Cheyenne, WY, 2008.
- Zellmer, Sandra. "United States: The Emergence of Environmental Considerations," *The Evolution of the Law and Politics of Water*, J.W. Dellapenna and J. Gupta (Eds.), Springer Science and Business Media B.V., pp. 205-23, 2009.
- Zilberman, D., A. Dinar, N. MacDougall, M. Khanna, C. Brown, and F. Castillo. *Private and Institutional Adaptation to Water Scarcity During the California Drought: 1987-92*, Staff Paper No. 9802, U.S. Department of Agriculture, Economic Research Service, p. 70, July 1998.