1. 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 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 roughly 85% of US consumptive water use, growing water demands with relatively fixed water supplies 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 increasing competing water demands (NRC, 1996; CBO, 1997; Schaible, 2000; Schaible et al., 2010). Historically, federal and state policy response has focused on agricultural water conservation and mandatory withdrawal restrictions, and more recently the use of water markets to meet the nation’s various water needs. Expanding water demands for energy development and other uses, together with shifting regional water balances under projected climate change, have heightened awareness of the importance of water conservation for the long-term sustainability of 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.

2. WATER SUPPLY AND DEMAND CHALLENGES FOR US IRRIGATED AGRICULTURE

The US 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 withdrawals 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 2013. Total water withdrawals peaked at about 482 million acre-feet (maf) in 1980 before declining slightly after 1985 to about 458 maf in 2005 (126% higher than in 1950) and declining further to 398 maf by 2010 (still 97% higher than in 1950 but a 13% decline since 2005) (Maupin et al., 2014). Water withdrawals for irrigated agriculture and thermoelectric power are the dominant sources of water demand. Nationally, water withdrawals for thermoelectric power (primarily for cooling purposes) have increased threefold since 1950, accounting for 45% of total US withdrawals in 2010 (about 180 maf). However, efficiency gains in thermoelectric cooling have reduced water demand in recent decades, contributing to a decline in withdrawals of 23% from peak demand in 1980 and 20% since 2005. Nearly 98% of water withdrawals for thermoelectric cooling systems currently return to their source of origin, where the water can be reused for other purposes, including irrigation.

Irrigated agriculture, with withdrawals of about 129 maf, accounted for 32% of the nation’s total in 2010. Irrigation withdrawals, while 29% greater than in 1950, have declined 23% from peak demand in 1980 and 9% below the level for 2005. For the 17 western states, where much of the nation’s irrigated production is concentrated, irrigated

1. Water withdrawals (one measure of water demand) refer to the quantity of water removed during a period of time from streams, rivers, lakes, reservoirs, and groundwater aquifers, for an intended use.
2. An acre-foot represents the water quantity required to flood 1 acre at 1 ft in depth, equivalent to 325,851 gal.
3. The 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 chapter as the 31 eastern states (or eastern states).
agriculture continues to account for most water demand from both surface water and groundwater sources (Maupin et al., 2014). In 2010, irrigation water withdrawals in the West totaled approximately 107 maf, or 64% of total water withdrawals in the region; irrigated agriculture accounted for 61% of surface water withdrawals and 72% of groundwater withdrawals across the region.4

2.1 Challenges Facing Irrigated Agriculture

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

2.1.1 Native American Water Rights

Native American reservation water rights were established by the US 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 federal government, even if those rights were not explicitly stated in the reservation treaty. In subsequent decisions, the US Supreme Court quantified those water rights as the water needed to irrigate all “practicably 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 US Supreme Court (in 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 rights to groundwater has been made, but some states recognize these rights (Gregory, 2008).

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. However, settlement of Native American water-right claims may not necessarily result in less water for agriculture, but rather a reallocation of existing water rights. While water delivered to reservation lands generally originates from existing water-right allocations, tribes through settlement arrangements are generally allowed to assign, exchange, or lease their water-right allocation. Within existing negotiated settlements, some reallocated water supports

4. Water 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, USGS estimates of consumptive water use were discontinued after 1995.
irrigation expansion on reservation lands, but Tribes may also 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, because of the political and financial challenges in negotiating or adjudicating water-right claims and a lack of ability to finance irrigation projects and related storage, exercising reservation water rights have 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

2.1.2 Instream (Environmental) Flows

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. Until relatively recently, water-flow needs for fish and wildlife 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 more complex (eg, minimal flow requirements for seasonal time durations by stream node) and 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,6 riparian wetlands, and migratory bird habitat, as well as exotic species control and local/regional economic development (Sophocleous, 2007; Zellmer, 2008; MacDonnell, 2009).

5. Under the Interior Department’s Indian Water Rights Settlement Program the federal government has refocused settlement of tribal water-right claims, emphasizing negotiated settlements (with congressional approval) rather than litigation (US BoR, 2012b). Congressional hearings have revealed that in the last dozen or so years many more tribal claims were settled via negotiation than through litigation (US Senate Committee on Indian Affairs, 2012). While many tribal water rights remain unquantified, these settlements help to enhance certainty in water-right allocations, which may also contribute to new investment in improved irrigation systems.

6. Use of 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.
Environmental flows will likely play an increasingly important role in the ongoing competition among alternative 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. Water demands for environmental flows very often exceed the historical “minimum instream flow” requirement, placing increasing pressures on limited water supplies. The following examples illustrate the rising importance of environmental water demands.

Stream and river restoration projects have become an important component of federal and state environmental management programs. Based on a review of these projects in the National River Restoration Science Synthesis database, the number of river restoration projects across the United States increased exponentially since 1990, costing more than $14 billion (1990–2004), averaging slightly more than $1 billion annually (Sophocleous, 2007; Bernhardt et al., 2005). These 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.

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 overappropriated basins. Many state water laws now recognize environmental flows as a beneficial use and allow state and nongovernmental organizations, including conservation and environmental groups, to lease, purchase, or donate water or water rights to enhance river flows (Sophocleous, 2007; MacDonnell, 2009). In one of the few studies conducted, Landry (1998) reported that from 1990 to 1997 about 2.4 maf of water was “leased, purchased, or donated for purposes of enhancing river flows in the Western United States.” This quantity represented about 5.2% of the surface water applied by irrigated agriculture in 1998.

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 Federal 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 has historically, in nondrought years, conveyed about 7.4 maf of water annually from the Sacramento, Trinity, American, Stanislaus, and San Joaquin Rivers to agricultural users (irrigating more than 3 million acres), municipal users, wildlife refuges, and for endangered fish species recovery in the Sacramento and San Joaquin Valleys and the San Francisco Bay/Delta Estuary. In 1992, the US Congress adopted the Central Valley Project Improvement Act, 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 (US BoR, 2009). The Act also reallocated 800,000 acre-feet of water from existing off-stream uses to fish and wildlife annually. Since 1992, and after nearly $1 billion has been spent on numerous restoration projects throughout the Central Valley, reallocating water supplies to meet environmental/

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7. The evolution and status of state-specific minimum instream environmental flow programs, statutes, and policies, which vary widely across the western states, has been summarized by MacDonnell (2009).
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 (US BoR, 2010).

2.1.3 Water for Energy Expansion

US energy sector growth, for production of fossil fuels, biofuels, and other renewable energy sources, is also expected to place increasing demand on water resources. In the western states, where surface water systems are already overappropriated and groundwater aquifer levels are declining in many areas, energy-related water demand is expected to affect local water supply/demand conditions with potential impacts on regional agricultural production.

An expanded biofuel sector requires water for both processing and feedstock 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 demand for irrigated feedstock production for biofuel production, however, is expected to be more significant. Chiu et al. (2009), in estimating the “embodied water in ethanol,” revealed that: (1) more corn production for ethanol was taking place within highly irrigated regions, particularly in the northern High Plains (Ogallala Aquifer) region; and (2) consumptive water use for bioethanol production in the United States (including water for irrigated feedstock crops) (measured in acre-feet equivalent units) increased from 1.54 to 4.95 maf (246%) between 2005 and 2008. The National Research Council (2008) estimated that: (1) irrigated corn for ethanol (in Nebraska) required about 780 gal 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 US Government Accountability Office estimated that corn ethanol production (adjusting for irrigation return flows) for the Northern Plains states consumed 323.6 gal of water per gallon of ethanol, with nearly 88% of this requirement estimated to come from groundwater (US GAO, 2009). 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; Malcolm et al.,

Expansion of corn acreage to meet biofuel feedstock demand would likely involve an increase in consumptive water use, particularly for the Plains states, both because of 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.

Water demands are also expected to increase because of growth and technical innovation forecast in other energy-related uses, including thermoelectric generating capacity, development of utility-scale solar power across the southwestern United States, and 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 continue 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 oil or 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, 2012). However, the practice has raised public concern for groundwater use and quality.

Increased use of evaporative cooling technology for thermoelectric and solar power may also 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 US Department of Interior are intended to address the uncertainties of water resource impacts for this sector. In a study of hydraulic fracturing water use, the USGS indicates that based on information from 263,859 oil and gas wells drilled between 2000 and 2014, water use varies significantly across well types (horizontal, vertical, or slanted), well depths, regions and their hydrologic and geologic characteristics, type of water used (saline or freshwater), as well as the volume and composition of the produced water originating from the oil and gas well itself (Gallegos et al., 2015). The USGS study indicates that as oil and gas production associated with fracking has increased, the median annual water volume used to hydraulically fracture horizontal wells increased from less than 670 m³ (176,995 gal) to nearly 15,275 m³ (4 million gal) per oil well and 19,425 m³ (5.1 million gal) per gas well. Because associated environmental problems are heavily linked to volumes of water used and produced by fracking wells, differences in local hydrologic, geologic, and fracking practices ultimately translate into significant differences in the potential for fracking-based wastewater environmental impacts.

For most new energy development, water quality and environmental impacts are potentially the more significant policy concern. Summarizing these demands is outside the scope of this chapter because of 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.9

2.1.4 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, 2014; US CCSP, 2008; Melillo et al., 2014; US BoR, 2012a). In much of the western United States, effective

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9. For more specific information on these water-use demands, see NETL, 2008; GWPC and All Consulting, 2009; US DOE, 2010; US GAO, 2010; Bartis et al., 2005; US BLM, 2011.
precipitation available for crop uptake 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, 2014; 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 reduced late season reservoir storage amounts from precipitation and late spring and summer snowmelt. In many areas, streamflow and reservoir storage effects are expected to reduce water supplies for traditional peak irrigation water demands during the summer and fall growing seasons.

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, 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 snowpack levels across the western states, decreases have been relatively larger at lower elevations. In addition, results from various climate simulation models or analyses based on multicentury tree-ring reconstruction (1490–1998) indicate that expected warming temperatures and precipitation changes will reduce streamflow in the Upper Colorado River Basin. Streamflow could decline by 8–11% by the end of the 21st century, with declines as high as 25% by 2030 and 45% by 2060 (Christensen and Lettenmaier, 2007; Hoerling and Eischeid, 2007; McCabe and Wolock, 2007).

The US Climate Change Science Program’s *Final Report of Synthesis and Assessment Product 4.3* (US CCSP, 2008), drawing on 2007 IPCC climate change assessments and other studies, 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%) in the western interior (particularly the Colorado and Great Basin areas). The Bureau of Reclamation (BoR) report to Congress (US BoR, 2011) further disaggregated climatic impact and hydrologic projections to eight reclamation river basins. For the Colorado Basin, this study indicates that the southern subbasins are expected to experience greater warming and a decrease in precipitation—while 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 subbasins. 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. However, reductions in runoff during the spring and early summer are expected to reduce reservoir levels and water supply deliveries during the irrigation season. In its 2012 Study Report, the US BoR projected that with warming temperatures and reduced snowpack, the mean annual natural flows for the lower Colorado River (at Lees Ferry) over the next 50 years could be reduced by nearly 9% (US BoR, 2012a).

The 2011 BoR report also indicates that warming temperatures are expected to be relatively uniform over the Columbia River Basin, with generally wetter conditions varying across subbasins (US BoR, 2011). Decreases in snowpack are expected to be more substantial over the western mountain ranges of the 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 subbasins. The BoR report 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 subbasins. The report also notes, based on some studies, that general warming effects across the basin appear to have the most influence on runoff and ultimately on basin water supplies.10

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% if temperatures increase by 4.5°F (2.4°C) (IPCC Report, 2007). Aquifer recharge rates could decrease by as much as 25% 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 processes are less well 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 long-run 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 caused by 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 are needed that go beyond concerns about groundwater-level fluctuations and also address groundwater uncertainties and processes occurring over multiple decades to improve our understanding of groundwater’s response to climate change (USGS, 2009).

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 western states.11 Even for northern-tier

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11. Crop 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 (Izaurralde 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.
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 on-farm water management issue. Crop ET may also shift with projected changes in crop biomass because of temperature stress, carbon fertilization, and other factors, with expected yield declines for some crop/regions (eg, for corn) and positive CO₂ impacts for other crop/regions (eg, for wheat). In the eastern United States, where precipitation is generally sufficient to support rain-fed 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.

2.2 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. Three critical questions include:

1. Can irrigated agriculture adapt to climate-adjusted water supplies and emerging water demands through conventional means alone (ie, 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?

2.2.1 Sustainability of US Western Irrigated Agriculture

Reduced water supplies because of climate change will likely further constrain already overallocated 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 effectively, that is, 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 because of higher evaporation rates caused by rising temperatures.

The critical link between climate change vulnerability and sustainability is adaptability (Wall and Smit, 2005; Hall et al., 2008; IPCC Report, 2007, 2014; Brekke et al., 2009; Marshall et al., 2015). Given growth in competing demands and projected climate

12. For purposes here and consistent with USDA reports, 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. Adaptation strategies involve various mechanisms for achieving agricultural water conservation and allocation goals.
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 more intensive use of field-level water management practices to enhance irrigation efficiency and potential farm water savings. Such practices may include broader 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 systems with surge flow/cablegation applications, 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). Broader use of tailwater pits may also be used to enhance capture and reuse of irrigation drainage from fields. Pressurized system enhancements, including low-energy precision application/drop-tube systems, drip/trickle and low-flow microspray irrigation systems, and automated nozzle control systems, also improve the precision of applied water while reducing energy requirements for pressurization.

Under 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 a 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 (Fereres and Soriano, 2007; Geerts and Raes, 2009). Thus appropriately integrating water management practices with efficient irrigation systems improve the adaptability of irrigated agriculture to water supply deficits, while enhancing long-run sustainability.

2.2.2 Sustainability of US 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. Nearly 80% of crop water applied in the eastern states is pumped from shallow aquifers subject to annual recharge that also often serve as the primary source for downstream surface water flows for nonagricultural uses (USGS, 2011a). Less than 6% of the water for eastern irrigated agriculture comes from off-farm water sources (USDA/NASS, 2014b).

13 While all irrigation is supplemental to rain-fed 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).
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 42% from 1998 to 2013 and by 14% since 2008 (USDA/NASS, 2014b). Irrigation has increased in the eastern states primarily because of increases in commodity prices and yields, increased risk avoidance because of recurring drought conditions, and access to available groundwater supplies at relatively low cost because of shallow aquifer pumping depths (Midwest Irrigation, 2010; Fischer Farm Services, 2011; Evett et al., 2003; Vories and Evett, 2010). 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. Expanded 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 nonagricultural uses, the lack of reliable surface water supplies because of limited reservoir storage capacity, rising irrigation pumping costs, and water quality concerns from irrigation system losses have all heightened concerns for on-farm water conservation as a critical component of a sustainable irrigated agriculture sector in the eastern states. As a result, advancing on-farm water conservation is as important throughout much of the 31 eastern states as it is in the 17 western states.

3. HOW IMPORTANT IS IRRIGATION TO US AGRICULTURE?

Nationwide, irrigated agriculture makes a significant contribution to the value of US agricultural production. In 2012, the market value of all agricultural products sold was $394.6 billion, with irrigated farms (farms with at least some irrigated cropland) accounting for roughly 39% of market sales, or $152.4 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 2012 was $187,097, the average value for irrigated farms was nearly 2.7 times higher, at $514,412. The average value of farm products sold by irrigated farms was nearly 3.9 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 2012, the total value of crop products sold (including nursery and greenhouse crops) by irrigated farms was $106.3 billion, representing 50.0% of the value of crop sales by all farms (Table 1). For irrigated farms only, the value of crop products sold accounted for nearly 70.0% of their agricultural sales in 2012, with livestock products accounting for the remainder. In general, nonirrigated farms were more dependent upon livestock and poultry, with livestock/poultry sales accounting for 56.2% of agricultural product sales.

14. The largest irrigation increases in the East since 1998 (though 2013) have been in the Southeast (Georgia at 85% and Alabama at 118%), the Lower Mississippi Delta (Missouri at 48%, Arkansas at 22%, and Mississippi at 53%), and the Upper Midwest (Minnesota and Michigan, each at 60%).

15. The relative importance of irrigated forage and feed production varies across states. In California, irrigated forage acres (alfalfa and other hay, grass silage, and greenchop) account for 88% of acres devoted to irrigated forage and corn production. In the Plains states, however, irrigated corn for grain acres dominate production acres for irrigated forage and corn for grain, ranging from 62% in Texas to 87% and 93% in Kansas and Nebraska, respectively (USDA/NASS, 2014a).
<table>
<thead>
<tr>
<th>Farm Characteristic</th>
<th>All Farms</th>
<th>Irrigated Farms (Mixed Irrigated and Dryland Cropland)</th>
<th>Farms With All Harvested Irrigated Cropland (no Dryland Cropland)</th>
<th>Dryland Farms (Farms With no Irrigated Cropland)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market value of agricultural products sold ($1000)</td>
<td>394,644,481</td>
<td>152,421,721</td>
<td>79,582,158</td>
<td>242,222,760</td>
</tr>
<tr>
<td>Average per farm ($)</td>
<td>187,097</td>
<td>514,412</td>
<td>471,687</td>
<td>133,603</td>
</tr>
<tr>
<td>Crops, including nursery and greenhouse crops ($1000)</td>
<td>212,397,074</td>
<td>106,281,346</td>
<td>57,540,345</td>
<td>106,115,728</td>
</tr>
<tr>
<td>Average per farm ($)</td>
<td>205,754</td>
<td>444,231</td>
<td>386,509</td>
<td>133,809</td>
</tr>
<tr>
<td>Livestock, poultry, and their products ($1000)</td>
<td>182,247,407</td>
<td>46,140,375</td>
<td>22,041,814</td>
<td>136,107,032</td>
</tr>
<tr>
<td>Average per farm ($)</td>
<td>181,419</td>
<td>433,614</td>
<td>502,504</td>
<td>151,541</td>
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<tr>
<td>Total farm production expenses ($1000)</td>
<td>328,939,354</td>
<td>123,022,726</td>
<td>64,792,431</td>
<td>205,916,628</td>
</tr>
<tr>
<td>Average per farm ($)</td>
<td>155,947</td>
<td>415,192</td>
<td>384,028</td>
<td>113,578</td>
</tr>
<tr>
<td>Energy-related expenses (excluding customwork) ($1000)</td>
<td>24,835,166</td>
<td>11,092,703</td>
<td>5,919,143</td>
<td>13,742,463</td>
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<tr>
<td>Average per farm ($)</td>
<td>7435</td>
<td>21,231</td>
<td>20,225</td>
<td>4876</td>
</tr>
</tbody>
</table>

3.1 Where Does Irrigation Occur and What Does It Produce?

In 2012, 55.8 million farmland acres were irrigated across the United States (52.1 million acres of harvested cropland and 3.1 million acres of pastureland and other cropland), accounting for about 14.3% of all cropland, and 6.9% of all cropland, pastureland, and rangeland. About 16.5% of US harvested cropland acres were irrigated, while only 0.8% of pastureland acres were irrigated (USDA/NASS, 2014a). Nearly three-quarters of US irrigated agriculture occurred in the 17 western states, including 71.0% of harvested irrigated cropland and 92.3% of irrigated pastureland.

For 2012, 12 leading irrigation states accounted for 76.2% of all irrigated acres, including harvested cropland, pasture, and other lands (Fig. 2). Nebraska’s 8.3 million irrigated acres led all other states (14.9% of the US total), followed by California with 7.9 million acres (14.1%), Arkansas with 4.8 million acres (8.6%), and Texas with 4.5 million acres (8.0%). Three eastern states—Arkansas, Mississippi, and Florida—were among the 12 leading irrigation states. Mississippi accounted for 1.7 million acres (3.0%) and Florida for 1.5 million acres (2.7%) of the total US irrigated area.

Irrigated agriculture and water use are not static; areas grow and decline over time, influencing regional demands for water, energy, and other inputs (Fig. 3). 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 (72% of the increase), with lesser increases occurring in the Mississippi Delta and Southeast regions (Arkansas, Mississippi, Missouri, and Georgia). Irrigated acreage expansion in these states was attributed to availability of water supplies, improved irrigation economics [partly because of higher crop yields and reduced water costs associated with more efficient irrigation systems (USDA/NRCS, 2006)], increased biofuel demand for

![Figure 2](http://www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1_Chapter_1_US/usv1.pdf)
corn, recurring regional drought conditions, and the prospect of future restrictions on new irrigation development (at least for Nebraska). California and Florida led the states where irrigated acres fell during this period (0.7 million and 0.3 million acres, respectively).

Florida’s irrigated acreage has been decreasing for a variety of reasons, including: (1) the reallocation of water supplies to restore the 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).

In California, irrigated acres have been declining because of: (1) increased use of pumping restrictions on water supplies from the San Francisco Bay–Delta Estuary to meet environmental regulations to protect endangered species; (2) continued urban growth (although more recently at a slower pace because of current economic conditions); and (3) reduced soil productivity because of 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 irrigated cropland (Ayars, 2010; California Department of Conservation, 2011).

16. Personal communication with Professor Raymond J. Supalla, University of Nebraska—Lincoln, Agricultural Economics Department.
17. Florida’s irrigated acreage has been decreasing for a variety of reasons, including: (1) the reallocation of water supplies to restore the 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).
18. In California, irrigated acres have been declining because of: (1) increased use of pumping restrictions on water supplies from the San Francisco Bay–Delta Estuary to meet environmental regulations to protect endangered species; (2) continued urban growth (although more recently at a slower pace because of current economic conditions); and (3) reduced soil productivity because of 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 irrigated cropland (Ayars, 2010; California Department of Conservation, 2011).
For the period 2007 to 2012, irrigated area had a net decline of 777,074 acres across the United States. The larger decreases occurred in Texas (521,000 acres), Colorado (351,000 acres), Nebraska (262,000 acres), and Oregon (215,000 acres), with smaller declines in California and New Mexico. The larger net gains in irrigated acres during this period occurred in Arkansas (343,000 acres) and Mississippi (283,000 acres), with smaller increases in Louisiana, Georgia, and Kansas. However, since about 1997, the dominant pattern of change across the United States reflects a shift in irrigated acreage from the 17 western states to the Delta and Southeast (with the exception of Florida).

Fig. 4 illustrates the longer-term changes that have taken place since the early 1980s in irrigated acres (Part A) and agricultural water applied (Part B) across United States Department of Agriculture (USDA) farm production regions. 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 (11.9 million acres in 2007) above acreage irrigated in the Pacific region (11.6 million acres). While both regions had a net decline in irrigated acres from 2007 to 2012, the Pacific region’s decline occurred at a slightly faster pace. Similarly, since 1997, irrigated acres in the Delta region surpassed acres irrigated in the Southern Plains. Since 1997, the largest contraction in irrigated acres has occurred in the more arid western Mountain, Pacific, and Southern Plains regions.

Agriculture in the Pacific region is the most dependent on irrigation, with about half (51%) of cropland acreage irrigated in 2012. Other arid western regions with sizable concentrations of irrigated cropland include the Mountain (30%), Northern Plains (12%), and Southern Plains (12%) regions. In the eastern states, irrigated acreage accounted for 44 and 25% of cropland in the warmer Delta and Southeast regions, respectively, but less than 5% 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 more water overall, in part because of higher application rates. Average per acre field-level water use for agriculture in the Pacific region was 2.8 acre-feet, compared with 2.0 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 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 (62%) of total agricultural water applied across the continental United States.

What does irrigated agriculture produce? Irrigated agriculture accounts for a share of harvested acreage for most US crops. Vegetable, orchard, and rice crops had the dominant share of their harvested acres irrigated in 2012, with 82% for orchards and 100% for rice and vegetables (USDA/NASS, 2014a). For all other crops, irrigated acreage accounted for less than half of US harvested acreage by crop, with shares ranging from 41% for cotton to 5% for oats.

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. Rice, vegetables, and orchard crops were the only crops in the West with more than 80% of their
FIGURE 4  Irrigated acres and agricultural water applied by USDA farm production region. (A) Acres irrigated (1982–2012) (Census of Agriculture Statistics, 1982–2012, National Agricultural Statistics Service, USDA. (Summarized by Economic Research Service, USDA)). (B) Agricultural water applied (1984–2013) (Farm & Ranch Irrigation Surveys, 1984–2013, National Agricultural Statistics Service, USDA. (Summarized by Economic Research Service, USDA)). USDA farm production regions: Pacific (Washington, Oregon, and California); Mountain (Montana, Idaho, Wyoming, Nevada, Utah, Colorado, Arizona, and New Mexico); Northern Plains (North Dakota, South Dakota, Nebraska, and Kansas); Southern Plains (Oklahoma and Texas); Lake states (Minnesota, Michigan, and Wisconsin); Corn Belt (Ohio, Iowa, Missouri, Indiana, and Illinois); Northeast (New Hampshire, Pennsylvania, Maine, Maryland, Rhode Island, Massachusetts, Delaware, Connecticut, Vermont, New York, and New Jersey); Appalachia (West Virginia, Tennessee, North Carolina, Virginia, and Kentucky); Delta (Louisiana, Arkansas, and Mississippi); and Southeast (South Carolina, Alabama, Georgia, and Florida).
harvested cropland acres irrigated in 2012 (USDA/NASS, 2014a). Cotton, peanuts, and sugar beets grown in the West also relied heavily on irrigation, but only 50–64% of harvested cropland for these crops was irrigated. As much as 65–95% of the harvested cropland acres for corn for grain, sorghum, soybeans, wheat, oats, barley, and forage crops (hay, haylage, grass silage, and greenchop) in the West were farmed using dryland production systems.

Fig. 5 illustrates the relative distribution of 2012 harvested irrigated acres by major crop category for both the western and eastern United States. Corn for grain and forage crops accounted for about 49% of all harvested irrigated crop acres across the West (Part A). However, corn for grain, soybeans, rice, and vegetables accounted for nearly 80% of harvested irrigated crop acres across the eastern states (Part B). Cotton accounted for an additional 10% of irrigated harvested acreage in the East. Relative to the western states, the irrigated cropping pattern in the eastern states reflects a much smaller share of irrigated acres for forage crops and wheat, and a larger share of irrigated acres devoted to rice and soybeans.


In 2013, irrigators across the western states applied about 72.9 maf of water for irrigated cropland production (for all “acres in the open,” but excluding water applied to horticulture under protection), averaging about 1.8 acre-feet per acre (af/ac) overall (Table 2). Much of this water (51%) originated from surface water sources, with the remainder (49%) supplied from wells used to pump groundwater from local and regional aquifers (USDA/NASS, 2014b). Surface water is drawn from both on-farm and off-farm sources. On-farm surface water from ponds, lakes, or streams and rivers on the farm account for roughly 10% of total agricultural water applied in the West, while off-farm water sources accounted for nearly 41% of total water applied. Water from off-farm sources is generally supplied 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 1.5 af/ac in 2013 (Table 2). In contrast, applied water averaged 1.7 af/ac for on-farm surface water and 2.2 af/ac 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 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 (54%) of agricultural water for crop production in the western states was applied using pressure irrigation (sprinkler, drip/trickle, and/or low-flow microspray) systems, with most of the remainder (42%) applied with gravity irrigation systems. Application rates using gravity systems, which are generally less water use efficient and more likely associated with lower-cost surface water, averaged about 2.3 af/ac

19. For more information on gravity and pressure (sprinkler) irrigation systems, see Irrigation and Water Use Glossary on the USDA/ERS website at: http://webarchives.cdlib.org/sw1 rf5mh0k/ http://www.ers.usda.gov/Briefing/WaterUse/glossary.htm.
### TABLE 2 Water Application Statistics for the 17 Western States, for “Acres in the Open”, by Type of Irrigation and Water Source, 2013

<table>
<thead>
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<th></th>
<th></th>
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<tr>
<td>Water applied:</td>
<td>72,896,810</td>
<td>30,970,461</td>
<td>42.0</td>
<td>36,144,815</td>
<td>50.0</td>
<td>3,276,408</td>
<td>4.0</td>
<td>2,505,126</td>
<td>3.0</td>
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<td>Average Application (acre-feet/acre):</td>
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<td>1.34</td>
<td></td>
<td>0.90</td>
<td></td>
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<table>
<thead>
<tr>
<th>Water Sourcea</th>
<th>Wells</th>
<th>Surface Water Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ground Water (Wells) (Acre-Feet)</td>
<td>On-Farm Surface Water (Acre-Feet)</td>
</tr>
<tr>
<td></td>
<td>Percent Ground Water</td>
<td></td>
</tr>
<tr>
<td>Water applied:</td>
<td>72,896,810</td>
<td>6,984,525</td>
</tr>
<tr>
<td>Average Application (acre-feet/acre):</td>
<td>1.83</td>
<td>1.68</td>
</tr>
</tbody>
</table>

while rates for sprinkler systems averaged 1.3 af/ac, and drip/trickle and/or low-flow/microspray systems averaged about 0.9 af/ac.

Irrigation water is generally pumped from groundwater wells, surface water sources, or from water-delivery ditches (canals), and may be conveyed under pressure to access irrigated fields. Pumps are also used to pressurize field-level sprinkler, drip/trickle, low-flow, and microspray systems for field application. As a result, producers typically incur significant energy expenses over and above typical crop production costs under nonirrigation production. Both capital expenses (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 2013, irrigated agriculture in the western states incurred nearly $2.2 billion in energy expenses for on-farm pumping of irrigation water (Table 3). Costs for pumping water varied by type of irrigation [including water applied to “acres-in-the-open” (for field crops or horticulture crops) versus water applied to horticulture crops under protection (eg, greenhouse structures)], and whether the water was pumped from groundwater or surface-water sources. Water pumped from wells and for pressurizing irrigation systems used to irrigate field crops averaged about $65 per irrigated acre, compared with $33 per acre for water supplied from a surface water source. To pump water from wells to irrigate horticulture crops grown in the open cost about $92 per acre and nearly $101 per acre when using surface water. Pumping water from wells to irrigate horticulture crops grown under protection cost about $190 per 10,000 square feet of area under protection, while costing $57 per 10,000 square feet when pumping surface water for horticulture under protection. Expenses for scheduled irrigation replacement and maintenance and repairs for on-farm irrigation systems in the West totaled nearly $852 million (averaging $99 per affected irrigated acre). Irrigation labor costs across the western states in 2013 totaled about $814 million ($671 million for hired labor and $142 million for contract labor). Hired labor for irrigation averaged about $27,042 per irrigated farm while contract labor for irrigation averaged $28,535 per farm. In addition, irrigators using off-farm water supplies paid nearly $742 million to purchase water from irrigation districts and other off-farm water suppliers. Purchased water costs across the West averaged about $74 per affected irrigated acre, or $33 per acre-foot of water. However, total variable irrigation costs can vary significantly across states and water sources. In 2013, the sum of energy costs for pumping irrigation water, the cost of water purchased from off-farm suppliers, and scheduled replacement and maintenance and repair costs ranged from $55 per acre in Montana to $386 per acre in California for field crop acres irrigated in the open. For horticultural crops irrigated in the open, the sum of these costs ranged from $58 per irrigated acre in Oklahoma to nearly $550 per acre in Nevada. Costs for hired and contracted irrigation labor also varied significantly across states, influenced heavily by the crops irrigated and quantity of labor required. For 2013, average contract irrigation labor costs ranged from $2250 per farm in North Dakota to over $75,000 per farm in Nevada. Average hired irrigation labor cost ranged from $6000 per farm in California to $42,000 per farm in Arizona.

20. In addition, irrigated production can often involve higher (nonenergy) input and harvest costs because of more intensive input use and higher yields relative to nonirrigated production.
**TABLE 3** Irrigation Cost Statistics for the 17 Western States, by Type of Irrigation and Irrigation Expense, 2013<sup>a</sup>

<table>
<thead>
<tr>
<th>Total Pumping Expenditures</th>
<th>Energy Expenses for Onfarm Pumping of Irrigation Water, Total and by Irrigation Category and Water Source&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Scheduled Irrigation Replacement and Maintenance/Repair Expenses</th>
<th>Purchased Water Costs for Off-farm Water Supplies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expenses per Irrigated Acre</td>
<td>Expenses per 10,000 sq.ft.</td>
<td>Average Cost per Irrigated Farm</td>
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<tr>
<td></td>
<td>For Operations With Only Acres in the Open</td>
<td>For Operations With Only Horticulture in the Open</td>
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<td>$1,000 dollars</td>
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<td></td>
<td>Water from Wells:</td>
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<td>Dollars per acre</td>
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<td>For Operations With Only</td>
<td>For Operations With Only</td>
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<td>Acres in the Open</td>
<td>Horticulture in the Open</td>
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<td>Dollars per acre</td>
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<td>Surface Water</td>
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<td>Surface Water</td>
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<td></td>
<td>Average Cost per Irrigated Farm</td>
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<td></td>
<td>Hired Labor:</td>
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<td>$1,000 dollars</td>
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<td>Contract Labor:</td>
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<td>$1,000 dollars</td>
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<td>Purchased Water Costs for Off-farm Water Supplies</td>
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<td>Average Cost Per Acre</td>
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<td>Total Purchased Water Expenses</td>
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<td>($1,000 dollars)</td>
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<td>Per Acre</td>
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<tr>
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<td>Per Acre-Foot</td>
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</tbody>
</table>

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<sup>a</sup> USDA, Economic Research Service calculations based on USDA, National Agricultural Statistics Service, 2013 Farm and Ranch Irrigation Survey.

<sup>b</sup> Includes expenditures for all energy sources (electric, natural gas, LP gas, propane, butane, diesel fuel, gasoline and gasohol), except for solar.

In the 31 eastern states, variable irrigation costs in 2013 were generally less than those for the western states. Average energy pumping costs for water pumped from wells ranged from $31 to $74 per acre for field crops and horticultural crops, respectively, to $120 per 10,000 square feet for horticulture crops irrigated under protection (USDA/NASS, 2014b). Energy costs for water pumped from surface sources ranged from $34 per acre for field crops irrigated in the open to $66 per 10,000 square feet for horticulture crops under protection. Pumping costs for water pumped from wells are lower in the eastern states because groundwater pumping depths are generally shallower. Purchased water costs averaged $36 per acre (or $41 per acre-foot). However, purchased water from off-farm sources in the eastern states account for less than 6% of water supplies for acres irrigated in the open, and about 14% of water supplies used to irrigate horticulture crops under protection. Irrigation labor costs averaged $12,687 per farm for hired labor and $16,095 per farm for contract labor (with an overall average of $23 per acre for affected irrigated acres, compared to $55 per acre in the western states). In the eastern states, costs for scheduled irrigation replacement and maintenance and repair costs were similar to those in the western states, averaging $107 per acre for affected irrigated acres.

4. 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% 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 because of 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 agriculture, along with increasing water demands from nonagricultural users, significantly intensified the competition for available water resources. Over time, federal and state resource conservation programs provided financial and technical assistance to promote adoption of more efficient irrigation systems, to improve irrigation returns and enhance the health and productivity of the resource base, and to help ensure a more sustainable future for small farm and rural 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, 2013; Schaible et al., 2010). Fig. 6 illustrates that between 1984 and 2013 a substantial shift has occurred across the western states away from gravity irrigation to pressure-sprinkler irrigation systems. In 1984, for example, 71% of crop agricultural water in the West was applied using gravity irrigation systems. By 2013, operators used gravity systems to apply just 41% of water for crop production, while pressure irrigation systems accounted for 59%, or an increase of 31 percentage points from 1984. By 2013, much of the acreage in more efficient pressure irrigation systems included drip/trickle or low-flow microspray

21. Sprinkler irrigation systems operating with greater than 60 pounds per square inch (PSI) of pressure.
systems, low-pressure sprinkler, and low-energy precision application systems. Adoption of improved (more efficient) irrigation systems contributed to reducing agricultural water use, as fewer acre-feet were required to irrigate a greater number of acres using these systems. From 1984 to 2013, total acres irrigated (in the open) across the West increased by 1.7 million acres (from 38.1 to 39.8 million acres), while water applied for this agricultural production declined by nearly 1.4 maf (from 74.3 to 72.9 maf).

On-farm 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). Water applied to crops but not used for 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.

What happens to irrigation water that leaves the farm (ie, water not beneficially consumed through crop production) and its ultimate impact on local or regional water supplies depends on the many factors that influence the hydrologic water balance for the

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22. This definition of crop irrigation efficiency is conceptually consistent with Howell’s (2003) “seasonal irrigation efficiency” and the “irrigation efficiency” 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 herbaceous windbreaks and cover crops.
watershed. Water balance accounts for where all the water within a watershed comes from and where it goes and is significantly influenced by soils, land cover, climate, water source, topography, and hydrologic characteristics both on and off the farm. Research demonstrates that while generally recognized as conserving water on the farm, improved on-farm irrigation efficiency may or may not contribute to water conservation at a basin scale (Clemmens et al., 2008; Evans and Sadler, 2008; Sadler et al., 2005; Fereres and Soriano, 2007; Geerts and Raes, 2009; CIT, 2011). This may require accompanying institutional measures that restrict agricultural consumptive use or reallocate efficiency savings within the basin. These studies do, however, reveal that improved on-farm irrigation can conserve water on and beyond the farm by:

1. reducing unnecessary evaporation and unwanted transpiration 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 (eg, land grading, snow fences, plant-row mulches, and furrow diking techniques);
3. reducing deep percolation water that is severely degraded in quality or uneconomic to recover;
4. reducing field runoff that is lost to the hydrologic system (ie, runoff water that is not accessible or reusable because of salinization or entry to a saline body);
5. reducing crop ET requirements for downstream irrigated agriculture (ie, by reducing saline return flows allows downstream irrigators to reduce their salt leaching requirements); and
6. reducing normal crop ET associated with crop stress under deficit irrigation (ie, the irrigator intentionally provides the crop with less than its full ET requirement, resulting in reduced yield but higher net economic returns).

These studies also indicate that, in many cases, conserved water to augment water supply in the river basin may not be the primary policy concern. Water conservation programs 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. 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, 2011b). Thus, even without adding to regional water supplies, water conservation programs encouraging improved on-farm irrigation efficiency can purposefully serve local and regional economic, water-quality, and environmental policy goals that contribute to farmer and societal welfare, improve fish and wildlife habitat, and reduce ecosystem and human health risks associated with environmental pollution. Such programs can also serve to help the USDA promote small farm, limited-resource, and socially disadvantaged farm policy goals.23

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23. For these programs, see the website at: http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/people/outreach/slbfr/.
The potential for continued improvement in on-farm irrigation efficiency to contribute to water conservation program goals relies a great deal on how efficient US irrigated agriculture is today. Because actual irrigation water use is rarely measured and actual consumptive use can vary significantly depending on agriclimatic conditions, the efficiency of irrigated agriculture (based on its traditional definition) cannot be readily measured. For an alternative measure, using farm-level data from USDA’s Farm and Ranch Irrigation Survey (FRIS) from 1994 to 2008, Fig. 7 illustrates the relative efficiency of irrigated agriculture for the 17 western states based on the shares of irrigated acres where water is applied using more efficient irrigation systems (separately for gravity and pressure-sprinkler systems). Between 1994 and 1998, the share of western irrigated acres using improved gravity-flow systems increased from 21% to 25%. During this time period, the share of irrigated acres using improved pressure-sprinkler irrigation also increased and accounted for about 23% of total irrigated acres in 1998. Thus more efficient irrigation in 1998 (based on a system-based definition, unadjusted for on-farm water management) accounted for nearly 49% of irrigation in the West. From 1998 to 2008, however, the share of gravity-flow irrigated acres using improved gravity systems declined. At the same time, improved pressure-sprinkler irrigated acres continued to increase, although at a slower rate than in the earlier period. FRIS evidence reveals that while substantial technological innovation has already occurred in western irrigated agriculture, significant room for improvement in farm irrigation efficiency exists—as traditional gravity or less efficient pressure-sprinkler systems still account for over 50% of irrigated acres. Similarly, potential for improvement exists for irrigated agriculture in the eastern states where traditional, less efficient systems irrigate at least 48% of irrigated acres (USDA/NASS, 2014b). Historical transitions suggest that, while US irrigated agriculture is on a path toward greater sustainability, further progress will likely be needed as water demand and supply conditions evolve.

However, adopting more efficient physical systems alone may not be enough in the face of increasing water scarcity, especially with new demands from climate change and an expanding energy sector. The sustainability of irrigated agriculture will depend increasingly on expanded adoption of more efficient “irrigation production systems” (Evans and Sadler, 2008; Sadler et al., 2005; Clemmens et al., 2008). A “production system” policy perspective encourages a continued shift from traditional, less efficient gravity/sprinkler irrigation to more efficient irrigation application systems, but with greater reliance on on-farm water management improvements that increase overall production efficiency beyond that normally attainable because of complementary investments in human capital, that is, helping farmers determine the optimal timing of irrigation and how much water to use by crop growth stage (Schaible et al., 2010). Improved on-farm 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, FRIS survey data suggest that producers give more emphasis to such conventional practices as reducing irrigation set times, alternating furrow irrigation (for row crops), and using end-of-field dikes to restrict field runoff (USDA/NASS, 1996, 2004, 2010, 2014b). Use of tailwater pits for on-farm water reuse has declined across gravity irrigation, from 22% in 1994 to 8% by 2008, partly in response to irrigation application improvements that limit field runoff. In 2013, the combined application of these conventional water management practices was used on only 23% of gravity-irrigated acres (USDA/NASS, 2014b). Total gravity-irrigated acres that have been laser leveled or zero graded have declined from 27% of acreage in 1998 to 15% in 2013.

By 2013, less water-intensive gravity management practices, such as use of special furrowing techniques, shortened furrow lengths, PAM, and use of surge-flow or cablegation irrigation, were applied on a relatively small portion (ranging from 3% to 7%) 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.

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 of the crop” or by “feeling the soil” for soil moisture content, or irrigation may be based on a calendar schedule or an “in-turn” (fixed rotation) delivery schedule for water supplied to the farm. For 2013, fewer than 12% of irrigators throughout the West used soil or plant moisture-sensing devices or commercial irrigation scheduling services (USDA/NASS, 2014b). Fewer than 2% 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 because these practices are much more human capital and management intensive than traditional water application decision tools. These more sophisticated tools

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24. The sustainability of irrigated agriculture could also be enhanced through continued research and development of crop cultivars with improved tolerance to drought, heat, and salts, as well as shorter growing seasons. However, this particular issue is beyond the focus of this chapter.
may require more extensive technical training and support to increase their adoption. Similar relationships exist for the eastern states, except that irrigation decisions for this region generally are not based on water delivered within a fixed rotation to the farm because less than 5% of the region’s irrigated acres use off-farm water sources.

Our findings suggesting significant potential for wider adoption of more efficient “irrigation production systems” are consistent with recommendations of the National Research Council report, *Toward Sustainable Agricultural Systems in the 21st Century* (NRC, 2010) and the USDA REE 2014 Action Plan (USDA REE, 2014). Both reports recommend the need for greater policy emphasis on integrating on-farm water conservation with watershed-level water management mechanisms that help facilitate optimal allocation of limited water supplies among competing demands, including use of conserved water rights, drought-year water banks, water option markets, contingent water markets, reservoir management, well drilling and/or groundwater pumping restrictions, and irrigated acreage retirement.25

Integrating agricultural water conservation programs with watershed-level water management tools allows for accounting for basin-level water balance by considering the fate of farm-level water savings/losses. Watershed-level water management tools help to create more efficient water allocations by encouraging basin stakeholders to recognize the opportunity value of water across competing uses and by facilitating water transfers through market-based trading and reallocation schemes.

5. IRRIGATION INVESTMENTS AND FUNDING SOURCES

While the need for continued improvements in water-conserving production systems in US irrigated agriculture is well established, water use efficiency gains depend primarily on irrigation investment decisions in the private farm sector. Approximately $2.6 billion was invested in irrigation systems in 2013 by irrigated farms across the United States (including both private expenditures and public funding assistance), compared with $2.1 billion in 2008 and $1.1 billion in 2003 (USDA-NASS, 2004, 2010, 2014b).26 On-farm irrigation investments have tended to focus on more precise water application that satisfies crop requirements while minimizing field losses. Total irrigation investments across the western states for 2013 ($1.9 billion) accounted for 72% of irrigation investments across the United States. Upgrades in application equipment and machinery in 2013 (at $1.4 billion) accounted for 71% of total irrigation investments in the western states. New well construction or deepening of existing wells accounted for the next largest farm-level investment in the West ($340 million, representing 18% of total irrigation investment regionally). In terms of

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25. “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.” In addition, USDA’s Strategic Plan for FY 2014–18 also highlights the importance of using farm-level, watershed, and institutional measures as a strategic means to meet this goal (USDA, 2015).

26. Total irrigation investment expenditures reported by FRIS include those made by the farm and “the portion of the expenditures made by or shared with others (landlords or government agencies). Including programs such as Environmental Quality Incentive Program (EQIP)” (USDA-NASS, 2014b). While FRIS information does not allow for separation of private versus publicly financed investment expenditures, it does indicate the share of farms using such financial assistance (discussed in the next paragraph).
investment purpose, scheduled investments for equipment/machinery replacement or main-
tenance accounted for the largest share of investments on western irrigated farms
($851 million out of $1.9 billion). Nationally, upgrades in irrigation facilities and equipment
specifically to improve water conservation accounted for $450.7 million in 2013 for the
western states and $70.3 million for the eastern states, or roughly 24% and 10% of regional
on-farm irrigation investment expenditures, respectively. The larger share (70%) of in-
vestments for land leveling or zero grading of cropland to improve the uniformity of applied
water with gravity-flow systems across the West occurred on existing irrigated acres
($74 million out of $106 million); investments in land leveling to establish new irrigated
acres accounted for less than 2% of total investment expenditures.

Most on-farm irrigation investment in the United States is financed privately. Of farms
reporting irrigation improvements in 2013, only about 11% received public financial assis-
tance. The Environmental Quality Incentives Program (EQIP), administered by USDA’s
Natural Resources Conservation Service (NRCS), is the nation’s primary source of funding
for agricultural conservation activities on working farms and ranches. In 2013, EQIP
accounted for 28% and 2% of farms reporting public financial assistance for irrigation in-
vestments across the western and eastern states, respectively. Other USDA financial
assistance programs (eg, Conservation Stewardship Program, Wetlands Reserve Program,
Conservation Reserve Program) accounted for 15% and 10% of farms reporting assistance
within the western and eastern states, respectively, with the remaining funding provided by
non-USDA programs (eg, Environmental Protection Agency, Bureau of Reclamation, as well
as state and local water management and supply district programs).

6. WATER CONSERVATION POLICY: A WATERSHED
PERSPECTIVE

USDA signaled a shift to a more watershed/institutional, stakeholder partnership focus for
implementing its agricultural water conservation activities with the Agricultural Water
Enhancement Program (AWEP) under the 2008 Food, Conservation, and Energy Act (2008
Farm Bill). AWEP, a voluntary conservation initiative, provided technical and financial
assistance to producers to implement practices on agricultural land to conserve surface and
groundwater and improve water quality. Producers applied for AWEP participation through
USDA/NRCS watershed-level partnership agreements. From 2009 to 2013, USDA’s NRCS
entered into 100+ AWEP partnership agreements involving 6886 producer conservation
contracts designed to enhance agricultural water conservation, with a total obligation
commitment of $331.4 million (82.3% for financial assistance and 17.7% for technical
assistance).28

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27. Irrigated farms reporting EQIP funding assistance represented 3% of all US irrigated farms making
irrigation investments in 2013. However, the statistics here represent irrigated farm participants in
EQIP only for 2013 and do not reflect program participation over time.
28. AWEP, operated under USDA’s EQIP program, involved numerous complex partnership agreements.
These partnerships ranged from providing producers with assistance to convert from gravity irri-
gation to low-pressure sprinkler irrigation, to using irrigated acreage and water use restrictions and
conserved water for instream flow uses, and to implementing managed drought-year water banks. For
a description of AWEP and its partnership agreements, see http://www.nrcs.usda.gov/wps/portal/nrcs/
detailfull/national/programs/?&cid=nrcs143_008334.
With passage of the Agricultural Act of 2014 (2014 Farm Bill), Congress established the broader USDA Regional Conservation Partnership Program (RCPP). RCPP is designed to help implement USDA resource conservation programs in a way that enhances farm land and water stewardship at the watershed/regional landscape scale. This program accomplishes this goal through USDA partnerships with farmers and other resource stakeholders within a watershed or multicounty/state region, leveraging federal, state, and local financial resources to assist producers with a broader set of land and water conservation activities designed to increase the restoration and sustainable use of soil, water, and wildlife and related natural resources across the landscape (USDA/NRCS, 2015). RCPP partnerships may include one or more of the following eligible partners: agricultural or silvicultural producer associations, farmer cooperatives or other groups of producers, state or local governments, American Indian tribes, municipal water treatment entities, water and irrigation districts, conservation-driven nongovernmental organizations, and institutions of higher education. Once established, eligible partnership participants, via actual conservation contracts or easement agreements, may include producers and landowners of agricultural land and nonindustrial private forestland.

For 2014–15, RCPP funded 114 approved projects at a total obligation of $361.0 million (20 projects through the national competitive pool at $142.9 million; 24 projects through the CCA pool at $125.8 million; and 70 projects through the state competitive pool at $92.3 million). The number of partners on a given project range from 1 to 46, but average about 13. RCPP project costs range from $100,000 to $17.5 million, but average $7.1 million for national competitive projects, $5.2 million for CCA projects, and $1.3 million for state competitive projects. Improving water conservation and water quality associated with irrigated agriculture were significant objectives across 22 projects, funded at $66.4 million or 18.4% of RCPP project obligations for the 2014–15 period. Irrigation-oriented projects accounted for 16.8% of national project funding (five projects), 19.6% of CCA project funding (six projects), and 19.2% of the state competitive project funding (11 projects). RCPP funding for 2016 projects is projected at $225 million with project proposal decisions expected by USDA's NRCS in early 2016. While the share of future RCPP funding involving irrigation water conservation/water quality objectives is yet to be determined, it is expected to play a continued prominent role in achieving USDA's landscape-based, resource conservation objectives.

Even with a watershed conservation focus, adoption of more efficient irrigation application systems will continue to be an important component of agricultural water conservation efforts. The sustainability of irrigated agriculture, however, could be further enhanced by more intensely integrating improved on-farm water management practices with high-efficiency irrigation application systems, that is, greater emphasis on promoting efficient

29. RCPP funding is allocated to partnership projects through three funding pools: (1) 25% for projects through a state competitive process administered by the USDA NRCS State Conservationist; (2) 35% to projects within one of up to eight Critical Conservation Areas (CCA’s) designated by the Secretary of Agriculture; and (3) 40% percent for projects established via a national competitive process managed by USDA. Project partners are required to contribute to the cost of the project, conduct outreach and education to eligible producers, and for assessing project effects. For more discussion of RCPP, see the website: [http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/farmbill/rcpp/](http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/programs/farmbill/rcpp/).

“irrigation production systems” rather than sole emphasis on efficient irrigation application systems. In addition, through collaborative federal, state, and local partnerships under USDA’s RCPP, integration of on-farm conservation efforts with watershed-level water management tools will 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 producers for water conservation gains, allows producers to balance yield declines with improvements in profitability through reduced costs of applying water and related inputs. Integrating on-farm conservation and federal/state institutional mechanisms (conserved water rights, drought-year water banks, contingent (option) water markets, reservoir management, as well as irrigated acreage and/or pumping restrictions) will likely also encourage producers and other stakeholders to interact jointly in determining market-based water reallocations.

Finally, 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. 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 components of a producer’s production decisions—crop choice, crop yield target, irrigation system type, and on-farm 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 will be required to address the complexity of water conservation policy issues and their impact on agricultural production and regional resource use and quality. 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.

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