Towards a Sustainable Future: The Dynamic Adjustment Path of Irrigation Technology and Water Management in Western U.S. Agriculture

By

Glenn D. Schaible, C. S. Kim, and Marcel P. Aillery
Economic Research Service, USDA

Contact:

Glenn D. Schaible
Resource & Rural Economics Division
Economic Research Service, USDA
1800 M Street, N.W., Rm. S4048
Washington, DC 20036-5831

Phone: (202) 694-5549
Email: schaible@ers.usda.gov

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Irrigated agriculture accounts for nearly half the value of U.S. crop sales and 80-90 % of consumptive water use in the U.S. However, competition for the use of agricultural water supplies has intensified. Population growth, ecological and environmental demands, and Native American water-right claims continue to drive water resource conflicts in many western States. More recently, climate change projections and water demands for a growing bio-fuels sector are placing new pressures on existing water allocations, heightening awareness of the importance of water conservation in irrigated agriculture. Many factors — producer, farm, economic, institutional, and environmental — influence irrigation water-management and technology-adoption decisions and their effect on Federal water conservation and water quality goals. Climate change and energy sector growth, in particular, raise important questions: (1) Can irrigated agriculture adjust to climate-adjusted water supplies and emerging water demands through adoption of conserving technologies, water-management practices, and/or crop shifts alone? (2) What changes in water institutions may be needed to complement water conservation policy to more effectively manage increasingly scarce water supplies for agriculture? And (3) how will these changes impact irrigated agriculture, resource use, the environment, and rural economies?

This paper examines the evolution in the sustainability of U.S. irrigated agriculture as emerging water demands place increasing pressures on conservation and reallocation of increasingly scarce water resources. Previous studies have drawn largely on single-year, cross-sectional data to examine technology adoption issues in agriculture, with technology defined as a discrete exogenous producer choice. Our research, by contrast, uses time-series data from

USDA's Farm and Ranch Irrigation Surveys (FRIS) compiled over a twenty-year period, covering survey years for 1984, 1988, 1994, 1998, and 2003. First, to characterize irrigated agriculture's adjustment path, we examine differential western regional trends in the adoption of water-conserving technology and water-management practices to increasing water scarcity. Second, we adapt a generalized cost-function based acreage allocation model of producer technology adoption decisions (Schaible, et al., 2009) to evaluate conserving irrigation technology adoption for surface-water irrigated agriculture across the West. Third, we develop a new analytic framework that endogenizes technology adoption for onfarm water management within the traditional dynamic-optimization framework for groundwater irrigated agriculture across the West.

In endogenizing irrigation water-use, our adoption model expands the producer technology choice set beyond the traditional irrigation system definition to include irrigation water management (and thereby, *deficit irrigation*) as a crop-production technology choice. Accounting for endogenous technical change that incorporates both physical system and water management dimensions improves measures of producer behavioral response to shifting water-supply conditions expected due to drought, climate change, and emerging water demands.

The remainder of the paper is organized as follows: in section two, we present the policy motivation for examining continued producer adoption of conserving irrigation technologies as a foundation for providing a sustainable future for western irrigated agriculture. In section three, Part A, we adapt the acreage allocation model in Schaible et al. (2009) to evaluate technology adoption across surface-water supplied irrigated agriculture; and in Part B, we incorporate this model into a new acreage-based technology adoption model within the context of a normative, dynamic economic framework for groundwater-irrigated agriculture. In section four, we summarize historical transitions that help define the adjustment path to increased sustainability within western irrigated agriculture. Finally, we conclude by providing summary comments and potential policy implications.

Study Motivation

Over the last three decades, irrigated agriculture in the Western U.S. has undergone a significant technological transition, from the use of conventional irrigation systems of comparatively low water-use efficiency[1] to increased adoption of more water and energy conserving irrigation systems. In 1978, there were 43.0 million irrigated acres in the 17 Western States, with 64.0 percent irrigated with gravity-flow systems and the remainder irrigated primarily with conventional sprinkler systems [high-pressure center-pivot, linear/mechanical-move, big-gun, and permanent-set systems with pressurization requirements exceeding 60 PSI (pounds per square inch) (U.S. Bureau of the Census, 1982). In contrast, western farms irrigated 39.9 million acres in 2003, applying 73.6 million acre-feet of water (53.5 percent and 46.5 percent from surface and groundwater sources, respectively), with only 41 percent of the acres irrigated with gravity-flow systems and 58 percent irrigated with pressurized sprinkler and drip/trickle irrigation systems (NASS, 2004). However, nearly 40.0 percent of sprinkler irrigated acres in 2003 were irrigated with more conserving low-pressure sprinkler systems, and drip/trickle irrigation accounted for 5.0 percent of total irrigated acres. This transition to more conserving irrigation, observed over a period of increasing scarcity in water resources attributable largely to expanding water demands from traditional non-agricultural sources (e.g.,

[1] Water use efficiency here is interpreted to represent the fraction of applied water used to meet crop consumptive use and other beneficial purposes. Water applied but not used for beneficial purposes is regarded as field loss, some portion of which may eventually return to the hydrologic system through surface return flow and aquifer percolation.

municipal, industrial, environmental, and Native American water-right claims), has helped prepare western agriculture for emerging challenges.

New pressures on regional water budgets have refocused attention on the increasing scarcity of water resources in the West and the sustainable use of water for irrigated agriculture. Climate change is expected to continue to alter both the supply and the demand for water throughout the West for all sectors, while energy sector growth, particularly for bio-fuels production, is also expected to increase demand for water resources. Of the two, climate change is likely to have the more dramatic impact. Water demand for a bio-fuel plant of a given size is generally known (an engineering relationship) and local (site-specific). This direct water demand is generally managed through market-based permanent lease or purchase agreements among known farms and the bio-fuel firm of interest. While total withdrawals for biofuel processing are comparatively low, local impacts on water resources may be significant. More significantly, the bio-fuels industry will likely also induce additional demand for water as producers respond to increased corn and soybean prices and expand irrigated corn and soybean acreage. On the other hand, climate change is expected to have a broader, and potentially more insidious impact on agriculture (while it is known to exist, it is not readily quantifiable from year to year), by affecting all of agricultural production (including all irrigated production).

Global climate change has been occurring for some time and is expected to continue well into the future. In the western U.S., a gradual warming of temperatures is expected to significantly shift the West's traditional source of freshwater supplies from winter precipitation (i.e., snowpack) to more frequent and intense early spring precipitation falling as rain. This shift is expected to dramatically alter the quantity and timing of associated stream flows, with more flow occurring in the early spring, reducing quantities available for reservoir storage (from reduced late spring and summer snowmelt), thereby reducing water supplies available to meet summer and fall traditional irrigation requirements. Studies conducted for the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC Report, 2007) reveal that: (1) "the fraction of annual precipitation falling as rain (rather than snow) increased at 74 % of weather stations studied in the western mountains of the U.S. from 1949 to 2004" (Knowles et al., 2006); (2) April 1 snowwater equivalent snow cover "has declined 15 to 30 % since 1950 in the western mountains of North America," (Mote et al., 2003 and 2005; Lemke et al., 2007); and (3) in the central Rocky Mountain region, stream flow over the last century has "decreased by about 2 % per decade" (Rood et al., 2005).

River basin specific studies indicate that expected increases in future warming trends are expected to exacerbate these water resource impacts. For the Upper Colorado River Basin (UCRB), Christensen and Lettenmaier (2006) applied forecasted changes in temperature and precipitation from 11 climate models and report an 8 – 11 percent decrease in UCRB runoff by the end of the 21st century. Hoerling and Eischeid (2007), after examining 42 climate simulations for the UCRB, report likely average decreases in UCRB streamflow of 25 percent by 2030, and 45 percent by 2060. McCabe and Wolock (2007), using a combined approach, including analyses based on a multi-century tree-ring reconstruction (1490-1998) of streamflow for the Colorado River basin and climate model simulations, report that warming temperatures (from 1˚ to 2˚C) would reduce mean water-year flows for the UCRB from 8 to 17 percent, respectively. They suggest that such flow changes would "increase the likelihood of failure to meet the water allocation requirements of the Colorado River Compact." Van Kirk and Naman (2008), accounting for increased irrigation withdrawals and consumptive use overtime, estimate that 39 percent of the observed decline in the July-October discharge of the Scott River within the Klamath River Basin is explained by regional-scale climatic factors. Furthermore, the authors' conclude that these climate-induced decreases in late-summer streamflows will, "at best, complicate the recovery of anadromous salmonids, and may, at worst, hinder their persistence." Climate change induced streamflow impacts will both directly and indirectly impact irrigation water supplies throughout the West, through reduced streamflows, as well as through increased competition for an increasingly scarce resource.

Groundwater, the primary water source for much of Plains States irrigated agriculture, and a supplemental water supply (during low-precipitation/drought years) for many other irrigated areas of the West, will also likely be affected by climate change. In a study conducted for the National Oceanographic and Atmospheric Administration (NOAA) and the National Science Foundation (NSF), Dettinger and Earman (2007) found that while there is a need for more extensive study, continued warming will thin snowpacks and raise snowline elevations, and mountain recharge rates can be expected to decline as recharge areas shrink and snowmelt available for soil infiltration declines. Hall, Stuntz, and Abrams (2008) indicate that climate change can be expected to reduce aquifer recharge and water levels, especially for shallow aquifers, because higher temperatures will increase evapo-transpiration, and with more precipitation occurring as rain subject to increased runoff, less will be available to percolate into aquifers. They reveal that for the Ogallala Aquifer region, groundwater recharge is expected to "decrease by more than 20 percent if temperatures increase by 4.5º F (2.4º C)" (IPCC Report, 2007). For the Ellensburg Basin of the Columbia Basin Plateau, aquifer recharge rates could decrease by as much as 25 percent (NWAG Report, 2000).

For the northern-tier western States, moderate warming conditions could potentially enhance crop evapo-transpiration (ET) efficiency for many crops, while for the southern-tier western States, moderate warming temperatures will likely reduce crop ET efficiency (IPCC Report, 2007; CCSP, 2008). Reduced crop ET efficiency will increase irrigation water demand; while for the more temperate regions, improved crop ET efficiency could reduce irrigation water demand. However, even for the northern-tier States, moderate warming conditions will likely still impact applied irrigation water demands, because with less water supply (due to reduced snowpack and more early-spring extreme rainfall events), irrigation timing of limited water supplies becomes a more critical crop/water-management issue. With even higher climate change induced temperatures, such conditions are expected to intensify and expand geographically the impact climate change will have on irrigation water demands.

The critical linkage between climate change vulnerability and the sustainability of western irrigated agriculture is most likely *adaptability* (Wall and Smit, 2005; Hall, Stuntz, and Abrams, 2008; IPCC Report, 2007; Brekke et al., 2009). Reduced water supplies due to climate change will further constrain already over-allocated western water resources through increased competition, particularly among agricultural, municipal, industrial, and ecological uses (IPCC Report, 2007). This increase in competition underscores the importance of the timing of irrigation applications, i.e., being capable of applying more limited water supplies at the time and in the amount needed to meet consumptive-use requirements by crop growth stage. In addition, with rising temperatures, high-pressure sprinkler and traditional gravity irrigation systems become even less efficient, with higher application losses associated with increased evaporation. Given occurring and projected climate changes, adaptability of western irrigated agriculture towards a more sustainable future will involve more extensive integration of conserving sprinkler and gravity irrigation systems with intensive infield water-management practices. Such practices may include the use of soil- or plant-moisture sensing devices, commercial irrigation scheduling services, and computer-based crop-growth simulation models that assist producers in deciding when and by how much to irrigate. Other practices useful for gravity-flow systems may include the use of tailwater pits and laser-leveled fields, reductions in irrigation set times, shortening of furrow lengths, use of alternate row irrigations, and use of polyacrylamide (PAM) (a water-soluble soil amendment that stabilizes soil and waterborne sediment), all practices that improve distributional uniformity, timing, and water reuse. For both sprinkler and gravity conserving irrigation systems, more intensive use of infield water-management practices enhances a producer's ability to apply a quantity of water much closer to a crop's consumptive-use requirement, at the time required for the appropriate crop growth stage. Appropriately integrating water-management practices with varied conserving irrigation systems broadens irrigated agriculture's adaptability, while enhancing long-run sustainability.

Even with the substantial technological innovation that has already occurred in western irrigated agriculture, there likely still exists significant room for improvement. Schaible (2004), using irrigation system acreage data from the 1998 FRIS, examined the relative range of "water-conserving/higher-efficiency" irrigation across the 17 Western States, separately for pressure-sprinkler and gravity-flow irrigation. The author's results indicate that water-conserving/higher-efficiency irrigation (based only on an irrigation system acreage definition, excluding water-management practices) ranges from 46 – 78 percent for pressure-sprinkler irrigation in the West, and from 40 – 57 percent for gravity irrigation. For both irrigation technology categories, the results suggest room for considerable conservation improvement in irrigation water-use efficiency. That is, while western irrigated agriculture is on a path towards sustainability, it nevertheless has not been fully attained.

This research will examine, from both positive and normative perspectives, producer irrigation technology adoption decisions and the adjustment path observed for conserving irrigation across western U.S. irrigated agriculture. The research will draw on data from the 1984, 1988, 1994, 1998, and 2003 FRIS surveys to examine the historical transition in the West from conventional pressure-sprinkler and gravity-flow irrigation systems to the adoption of more conserving/higher-efficient irrigation production systems. Multiple conserving-irrigation technology categories will be defined for both pressure-sprinkler and gravity-flow irrigation. Each of these technology categories will also integrate FRIS information on producer use of onfarm conserving water-management practices. From a positive economic perspective, project research will integrate univariate analysis across conventional and conserving irrigation technology categories with the estimation of a generalized, cost-function based acreage allocation model to evaluate the economic, resource, and farm factors influencing producer irrigation production technology decisions for surface- water irrigated agriculture. From a normative economic perspective, we will then extend this generalized acreage allocation model and develop a new analytic framework that endogenizes technology adoption (incorporating water management) within the traditional dynamic-optimization framework for groundwater irrigated agriculture. This new dynamic framework will expand the producer's technology/water-management choice set beyond the traditional irrigation system definition to include irrigation water-management, including deficit irrigation choices.

Endogenizing dynamic technology adjustments: (1) expands our ability to evaluate the impacts of alternative conservation/water-management strategies in response to increasingly scarce water supplies; (2) helps to differentiate agricultural water demand adjustments more appropriately between general economic and policy-induced behavioral changes; and (3) significantly improves upon measurements of social welfare benefits and costs of alternative public resource policies. These measurement improvements can facilitate optimal water resource reallocation by helping public decision-makers differentiate between the need for improved water conservation policy versus institutional change in water resource management.

The empirical models for this research will be estimated using USDA FRIS data. FRIS is a farm-level irrigation production-practice and water-use survey that is conducted roughly every five years by USDA's National Agricultural Statistics Service (the year following USDA's Agricultural Census). FRIS is the most comprehensive source of consistent national data on the U.S. irrigated crop sector. Sample sizes ranged from 17,311 irrigated farms for the 1988 FRIS to 25,014 farms for the 2003 FRIS. In Part A of the following section, we adapt the Schaible et al. (2009) generalized, cost-function based acreage allocation model to evaluate factors influencing producer irrigation technology decisions for surface-water irrigated agriculture, and in Part B, we develop the acreage-based, dynamic technology adoption framework for groundwater irrigated agriculture.

Model Development

Part A: Technology Adoption for Surface-Water Irrigated Agriculture

Recognizing both conceptual and empirical limitations inherent with traditional probabilistic technology adoption models, Schaible et al. (2009) extend the dual approach established by Kim et al. (2005) and develop a generalized, cost-function based acreage allocation model to evaluate producer production technology adoption decisions. With no loss of generality, this model is easily adapted to evaluate the technology/water-management decisions of surface-water irrigators across western irrigated agriculture.

Assuming producers minimize cost, and assuming linearly homogeneous production functions, an estimable econometric acreage supply function for the j^{th} irrigation production technology, consistent with the theoretical framework specified in Schaible et al. (2009), can be specified as:

$$(1) \qquad A_j(y_j) = exp\left\{\psi_0 + \sum_z \sum_i \tilde{\beta}_i (p_z) D_i \left(\frac{(p_z)}{P_y}\right) + \sum_{i=1}^{m-1} \delta_i D_i\right\} + \varepsilon_j ,$$

where $A_j(y_j)$ and y_j are irrigated crop acreage and per acre yield, respectively, for the j^{th} irrigation technology/water-management production system, (p_z) is the unit price for the z^{th} input, P_y is output price, ψ_0, $\tilde{\beta}$, and δ are parameters, D_i is a dummy variable associated with the i^{th} irrigation production technology, ε_j is an iid random disturbance term, and where $\tilde{\beta}_j (z)[(p_z)/P_y]$ = $[\partial \ln A_j(y_j)/\partial \ln (p_z)]$ so that $\sum_z \sum_j \tilde{\beta}_j (p)[(p_z)/P_y] \neq 0$ also implies that the j^{th} irrigation production technology is non-homothetic (Schaible et al. 2009).

Farm-level irrigation technologies vary widely in their efficiency potential. Uncontrolled flood irrigation, widely recognized as the least efficient irrigation system, is generally below 50 percent but could potentially be as low as 35 percent (Negri and Hanchar, 1989). In general, application efficiencies for gravity-flow systems can range from 35 to 80-85 percent, with higher efficiencies obtained under improved gravity systems. These improved systems may involve improved distribution of water across a field using furrows, between borders, or within a basin; reduction of conveyance loss through use of a lined or piped field water-delivery system, improved uniformity of applied water on laser-leveled fields; use of cablegation or surge-flow water application, alternate-row irrigation, and limited-irrigation set times to enhance water infiltration; use of water capture and reuse techniques such as furrow-diking and tailwater reuse pits; and/or the use of polyacrylamide to reduce sediment runoff while enhancing moisture infiltration. Pressure or sprinkler-based system efficiencies can range from 50 to 90-95 percent, with the more conserving low-pressure systems – including low-energy precision application (LEPA) and drip/trickle systems – capable of efficiencies as high as 85-95 percent.

For gravity-flow and pressure-sprinkler systems, producers can also improve their irrigation efficiency by integrating practices within their production system that address irrigation water-management intensity; that is, the level at which producers apply water management at the intensive margin, often characterized based on the degree of sophistication used in determining when to apply irrigation water and at what quantity. The more conventional means of deciding when to apply water may involve “observing the condition of the crop” or “feel of the soil”; using a predetermined “irrigation crop calendar schedule”; applying water when delivered to the farm “in-turn” by the local water-supply organization (usually the local irrigation district); or applying water based on available media reports on crop water needs given local weather conditions. The more sophisticated (and conserving) means of deciding when to apply irrigation water include such practices as the use of soil- or plant-moisture sensing devices, commercial or government irrigation-scheduling services, and use of computer-based crop-growth simulation models.

For both pressure-sprinkler and gravity-flow irrigation production systems that include infield water-management practices, the higher the irrigation-application efficiency, the more water-conserving the irrigation technology tends to be. Higher efficiencies can translate into the need for even greater net reductions in water withdrawals when conservation improvements are combined with institutional restrictions on the use of water savings (Schaible and Aillery, 2003). In addition, because of reductions in runoff and reduced deep percolation that can transport sediment, nutrients and pesticides, water-conserving irrigation production systems also induce environmental benefits, reducing agricultural pollutant discharge loads to streams, lakes, and aquifers.

Using 2003 FRIS data, we will estimate this model for surface-water irrigated agriculture, defined for four irrigation technology/water-management production systems, specifically for irrigated acres associated with fields where producers use: (1) either conventional gravity-flow and/or conventional pressure-sprinkler irrigation systems; (2) improved gravity-flow irrigation systems and apply conventional water-management practices; (3) improved pressure-sprinkler irrigation systems along with conventional water-management practices; and (4) improved gravity-flow or improved pressure-sprinkler irrigation systems, as well as intensive infield water-management practices.

Part B: Technology Adoption for Groundwater Irrigated Agriculture

Groundwater irrigated agriculture makes use of similar irrigation systems and water-management practices as does surface-water irrigated agriculture. However, because the cost structure for groundwater irrigation involves a dynamic relationship that accounts for increased pumping costs associated with generally declining aquifer table levels over time and increased resource opportunity costs associated with a common-pool property, the conceptual framework for an acreage-based technology adoption model for groundwater irrigation is somewhat unique.

We begin by specifying a consumptive-use based crop production function. So, let the per acre crop production (y) be a quadratic such that:

(2) $$y(W) = a_0 + a_1 W - a_2 W^2,$$

where a_0, a_1, and a_2 are non-negative parameters, and W represents the per acre consumptive-use component of irrigation water (units: acre-feet of pumped groundwater for the irrigated crop).

Assume that the irrigation-efficiency relationship for the irrigation water applied using the ith irrigation technology is given by:

(3a) $$W = k_i W_i, \quad \text{for all } i, \quad 0 < k_i \leq 1,$$

where k_i represents the rate of applied irrigation efficiency associated with the ith irrigation technology, and W_i is the actual rate of irrigation water applied (per acre) with the ith irrigation technology. The per acre crop production relationship can then be restated as:

(3b) $y(W_i) = a_0 + a_1[k_iW_i] - a_2[k_iW_i]^2.$

Now, let total crop production be represented by:

(4) $$Y = \sum_{i=1}^{n} y_i\,(k_iW_i)\,A_i(\frac{P_w}{P_y}),$$

where A_i is the acreage associated with the ith irrigation technology, y_i is crop yield per acre with the ith irrigation technology, P_w is pumping cost per acre-foot of groundwater, and P_y is a unit output price.

Let the total profit function relationship be specified as:

(5) $$\pi = P_yY - P_w\sum_{i=1}^{n} W_i\,.$$

where total profit is based on total output, and the cost side is based on total applied water. The irrigation water demand relationship is then derived as follows:

(6a) $$\begin{aligned} P_w &= P_y\,(\frac{\partial Y}{\partial W_i}) \\ &= P_y\,[A_i(\frac{\partial y_i}{\partial W_i}) + y_i(\frac{\partial A_i}{\partial P_w})(\frac{\partial P_w}{\partial W_i})] \\ &= P_y\;A_i(\frac{\partial y_i}{\partial W_i})\,(1 + \frac{\varepsilon_i\eta_i}{\varphi_i}) \\ &= P_y\,A_i(1 + \frac{\varepsilon_i\eta_i}{\varphi_i})(k_ia_1 - 2k_i^2a_2W_i) \quad \text{using (3b)} \end{aligned}$$

(6b) $$P_w = P_y\,A_i(1 + \frac{\varepsilon_i\eta_i}{\varphi_i})k_ia_1 - 2\,P_y\,A_i(1 + \frac{\varepsilon_i\eta_i}{\varphi_i})\,k_i^2a_2W_i \qquad \text{for i = 1, . . ., n}$$

where $\varepsilon_i = (\frac{\partial A_i}{\partial P_w})(\frac{P_w}{A_i})$ represents an acreage response elasticity, $\eta_i = (\frac{\partial P_w}{\partial W_i})(\frac{W_i}{P_w})$ represents the flexibility of water demand, and $\varphi_i = (\frac{\partial y_i}{\partial W_i})(\frac{W_i}{y_i})$ represents the output elasticity for water.

Equation (6b) reflects a water demand curve for the *i*th irrigation technology. Figure 1 illustrates the acreage effect of technology-specific water demand shifts as water price (pumping cost), P_w, increases. Because the acreage effect is embedded in both the intercept and slope terms of each technology's water demand, with an increase in water price, water demand for furrow systems rotates downward from curve F_1 to curve F_2, while the water demand curve for sprinkler systems rotates upward from S_1 to S_2. At a water price P_{w_0}, furrow system water demand is at (f_1) and sprinkler system water demand is at (s_1), on curves F_1 and S_1, respectively. As water price increases to P_{w_1}, water demand for furrow systems declines to (f_2) on curve F_2 and water demand for sprinkler systems shifts to (s_2) on curve S_2. These water demand shifts reflect the corresponding shift to fewer furrow irrigated acres and more sprinkler irrigated acres, as well as the changes in water use per acre.

We can evaluate a measure for the net social benefits of an increase in pumping cost. To begin, the social benefits (SB) resulting from irrigation water use are represented by:

(7) $$SB = \sum_{i}^{n} \int_{0}^{W_i} [\, P_y A_i (1 + \frac{\varepsilon_i \eta_i}{\varphi_i}) k_i a_1 - 2P_y A_i (1 + \frac{\varepsilon_i \eta_i}{\varphi_i}) k_i^2 a_2 x_i \,]\, dx_i,$$

where x_i is a variable of integration.

Total pumping costs (TC) are represented by:

(8) $$TC = \sum_{i=1}^{n} C(SL - h) A_i W_i,$$

where C = a pumping cost per acre-foot of water per foot of lift, SL = the elevation in feet of the field surface level above sea level, and h = the water table elevation in feet above sea level.

Then the net social benefits (NSB) are represented by equation 9, as follows:

(9) $$\text{NSB} = \sum_{i}^{n} [\, P_y \,(1 + \frac{\varepsilon_i \eta_i}{\varphi_i}) k_i a_1 - C(SL - h)] A_i W_i \; - P_y \, A_i (1 + \frac{\varepsilon_i \eta_i}{\varphi_i}) \, k_i^2 a_2 W_i^{\,2} \,.$$

As pumping costs rise, farmers adapt by reducing water application per acre and/or by switching to more efficient irrigation technologies.[2] Equation (9) can be used to evaluate the water application rate that maximizes profits. However, equation (9) does not explain how farmers switch to improved irrigation technologies. To accomplish this, we re-specify equation (1) as follows:

(10) $$A_i = exp \, [\alpha_0 + \alpha_{1i} (\frac{P_w}{P_y})].$$

Here, α_{1i} can be positive or negative. For a less efficient irrigation technology, α_{1i} is expected to be negative (meaning that acreage for that technology would decline), and for a more conserving irrigation technology, α_{1i} is expected to be positive (acreage for that technology increases).

Inserting equation (6b) into equation (10) and rearranging terms results in the following relationship (which implies that water applied affects irrigation technology-specific acreage adjustments):

(11) $$(\frac{\ln A_i - \alpha_0}{\alpha_{1i} A_i}) = (1 + \frac{\varepsilon_i \eta_i}{\varphi_i}) k_i a_1 \; - \; 2(1 + \frac{\varepsilon_i \eta_i}{\varphi_i}) \, k_i^2 a_2 W_i \,, \quad \text{for } i = 1, \ldots, n.$$

Using the above information on the present value of net social benefits (from equation 9) and on technology-specific acreage responses (from equation 11), we can formulate the dynamic optimization model that endogenizes acreages associated with irrigation technologies as follows:

[2] First, here the "more efficient irrigation technology" includes consideration of potential use of deficit irrigation. Second, in reality, farmers may also adjust to increased pumping costs by switching to irrigate a crop with a lower consumptive-use requirement or to not irrigate the field at all, i.e., generally switching to a dryland crop alternative. However, this new model is presently specified only for a single crop. Future specifications will expand the model to the multi-crop case.

$$\text{(12) Max } Z = \int_{t=0}^{\infty} \exp(-rt) \sum_{i}^{n} \{[P_y(1+\frac{\varepsilon_i\eta_i}{\varphi_i})k_i a_1 - C(SL-h)]A_i W_i - P_y A_i(1+\frac{\varepsilon_i\eta_i}{\varphi_i})k_i^2 a_2 W_i^2\}\, dt$$

Subject to the following constraints:

$$(13) \qquad \frac{\partial h(t)}{\partial t} = \frac{R + (\delta - 1)\sum_{i=1}^{n} A_i W_i}{E \bullet S}, \qquad \delta \le k_i;\quad 0 \le t < \infty$$

$$(14) \qquad (\frac{\ln A_i - \alpha_0}{\alpha_{1i} A_i}) = (1+\frac{\varepsilon_i\eta_i}{\varphi_i})k_i a_1 - 2(1+\frac{\varepsilon_i\eta_i}{\varphi_i})k_i^2 a_2 W_i, \quad \text{for } i = 1, \ldots, n,$$

(15) $h(t = 0) = h_0$ where h_0 represents the initial water table level, and

where R = the aquifer recharge rate, δ = the rate of the return flow, E = the size of aquifer (acres), S = a storativity coefficient for the aquifer, t is a time variable, and r is the discount rate.

Equations 14 and 13 illustrate that water use affects irrigation technology acreage relationships and the aquifer water table level, respectively, while both measures also affect net social benefits accounted for in equation 12. So, when water price (pumping costs) change, producer responses affect both W_i and A_i, and then subsequently, these effects alter all other welfare measures.

The Lagrangian-Hamiltonian equation for this dynamic model is represented as follows:

$$(16) \qquad H = e^{-rt}\sum_{i}^{n}\{[P_y(1+\frac{\varepsilon_i\eta_i}{\varphi_i})k_i a_1 - C(SL-h)]A_i W_i - P_y A_i(1+\frac{\varepsilon_i\eta_i}{\varphi_i})k_i^2 a_2 W_i^2\}$$

$$+ \lambda[\frac{R + (\delta - 1)\sum_{i=1}^{n} A_i W_i}{E \bullet S}] + \sum_{i}^{n} u_i[(\frac{\ln A_i - \alpha_0}{\alpha_{1i} A_i}) - (1+\frac{\varepsilon_i\eta_i}{\varphi_i})k_i a_1 + 2(1+\frac{\varepsilon_i\eta_i}{\varphi_i})k_i^2 a_2 W_i],$$

where λ is an adjoint variable, u_i (i = 1, 2, . . . , n) is the Lagrangian multiplier, W_i (i = 1, 2, . . . , n) is a control variable, A_i (i = 1, 2, . . . , n) is a decision variable, and h is a state variable.

The necessary conditions for optimality, which hold for all i, are given as follows:

(17-1) $$\frac{\partial H}{\partial W_i} = e^{-rt}\{P_y A_i(1+\frac{\varepsilon_i\eta_i}{\varphi_i})k_i a_1 - CA_i(SL-h) - 2P_y A_i(1+\frac{\varepsilon_i\eta_i}{\varphi_i})k_i^2 a_2 W_i\}$$

$$+\lambda[\frac{(\delta-1)A_i}{E \bullet S}] + u_i[2(1+\frac{\varepsilon_i\eta_i}{\varphi_i})k_i^2 a_2] = 0, \qquad (\text{for } i = 1, 2, \ldots, n).$$

(17-2) $$\frac{\partial H}{\partial A_i} = e^{-rt}\{P_y(1+\frac{\varepsilon_i\eta_i}{\varphi_i})k_i a_1 W_i - P_y(1+\frac{\varepsilon_i\eta_i}{\varphi_i})k_i^2 a_2 W_i^2\}$$

$$+\lambda[\frac{(\delta-1)W_i}{E \bullet S}] + u_i[\frac{\frac{(\alpha_{1i}A_i)dA_i}{A_i} - \alpha_{1i}(\ln A_i - \alpha_0)}{(\alpha_{1i}A_i)^2}] = 0, \quad (\text{for } i = 1, 2, \ldots, n).$$

(17-3) $$-\frac{\partial H}{\partial h} = -e^{-rt}\sum_{i=1}^{n} CA_i W_i = \frac{\partial \lambda}{\partial t},$$

(17-4) $$\frac{\partial H}{\partial \lambda} = [\frac{R + (\delta-1)\sum_{i=1}^{n} A_i W_i}{E \bullet S}] = \frac{\partial h(t)}{\partial t}.$$

(17-5) $$\frac{\partial H}{\partial u_i} = (\frac{\ln A_i - \alpha_0}{\alpha_{1i}A_i}) - (1+\frac{\varepsilon_i\eta_i}{\varphi_i})k_i a_1 + 2(1+\frac{\varepsilon_i\eta_i}{\varphi_i})k_i^2 a_2 W_i, \quad (\text{for } i = 1, 2, \ldots, n).$$

(17-6) $$\lim_{t\to\infty} \lambda = 0 \quad \text{and} \quad \lim_{t\to\infty} \lambda h = 0.$$

Equation (17-1) assures that the optimal water use with a particular irrigation technology equates its marginal benefits to its marginal pumping costs plus marginal user costs and the opportunity costs associated with acreage allocations. Equation (17-2) equates the social benefits to the sum of user costs associated with increased pumping costs and the opportunity costs associated with acreage allocations for the ith irrigation technology. Equation (17-3) represents the adjoint equation, reflecting the fact that groundwater pumping creates the value associated with user cost. Equation (17-4) represents the equation of motion. Equation (17-5) represents an acreage response function associated with groundwater use for each technology. Equation (17-6) is the conventional transversality condition, which must hold in the limit as time approaches infinity.

Irrigation Technology/Water-Management in the West: Towards a More Sustainable Future

Prior to the 1970's, furrow and flood irrigation systems were the dominant production systems for western irrigated agriculture. By 1978, sprinkler irrigation — including center-pivot systems — accounted for about 35 percent of crop irrigation in the West. Virtually all of this transition involved adoption of high-pressure sprinkler irrigation. While the center-pivot system improved infield irrigation efficiency, water conservation was not the primary motivation for its widespread adoption. Other characteristics, such as yield enhancement (due to enhanced field uniformity in applied water) and the ability to extend irrigated agriculture to productive lands beyond traditional riparian boundaries, were the primary objectives behind the early transition from gravity-flow irrigation to center-pivot sprinkler irrigation. However, this expansion in irrigated agriculture brought with it additional problems, i.e., competitive resource allocation issues. With increased population growth in the West, the advent of the environmental age, and increased judicial efforts to honor Native American water rights, significant water policy analyses since the early 1980's have recognized the merits of new regulatory, conservation, and water market policies designed to mitigate water resource allocation conflicts (Hamilton, et al., 1989; Hornbaker and Mapp, 1988; Howe, 1985; Martin, 1986; Moore, 1991; Schaible, 2000; Peterson et al., 2003; Kim et al., 2000; Schaible and Aillery, 2003). But producers themselves, with assistance from Federal and State resource conservation programs, have adopted conserving irrigation production systems to improve irrigation returns, enhance the health and productivity of their resource base, and ensure a more sustainable future for their livelihoods.

Using data from the FRIS, compiled over two decades (1984-2003), we evaluate the transitions in western irrigated agriculture from conventional to conserving irrigation systems by summarizing: (1) irrigated acres and agricultural water use for three alternative definitions of "conserving irrigation" and (2) producer adoption of conserving water-management practices. The alternative definitions for conserving gravity (GRV) irrigation systems, from least to most conserving, include:

Conserving GRV-1 ─ furrow gravity irrigated acres using an above- or below-ground pipe, or a lined open-ditch field-water delivery system.

Conserving GRV-2 ─ gravity irrigated acres in GRV-1, plus acres for flood irrigation (between borders or within basins) for farms using laser-leveling, and using a pipe or lined open-ditch field-water delivery system.

Conserving GRV-3 ─ gravity irrigated acres in GRV-1, plus all flood irrigated acres for farms using laser-leveling, and field water supplied through an above- or below-ground pipe or lined open-ditch field-water delivery system.

Separately, for each of these definitions, all other gravity-flow irrigated acres were classified as consistent with a conventional gravity irrigation system.

The three alternative definitions for conserving pressure-sprinkler (SPK) irrigation systems, from least to most conserving, include:

Conserving SPK-1 ─ acres irrigated using only drip/trickle irrigation systems.

Conserving SPK-2 ─ acres irrigated in SPK-1, plus acres irrigated using low-pressure sprinkler irrigation systems (PSI < 30).

Conserving SPK-3 ─ acres irrigated in SPK-1, plus acres irrigated using either low- or medium-pressure sprinkler irrigation systems (PSI < 60).

Separately, for each of these definitions, all other pressure-sprinkler irrigated acres were classified as consistent with a conventional pressure-sprinkler irrigation system. For gravity and pressure-sprinkler irrigation, respectively, GRV-1 and SPK-1 are designed to reflect a lower-bound for conserving irrigation, while GRV-3 and SPK-3 reflect an upper-bound.

Results for both conserving gravity and conserving pressure-sprinkler irrigation for FRIS survey years (from 1994 through 2003) are summarized in Table 1 (for acres irrigated) and Table 2 (for agricultural water use).[3] [FRIS results for 2008 will not be available until late 2009.] Results highlight several significant transitions that have occurred in irrigated acres, technology, and water use over the past 25 years in western irrigated agriculture. Of the 39.1 million acres irrigated in 1984, 62.0 percent were irrigated with a gravity-flow system. In 2003, of the 39.9 million acres irrigated, only 41.0 percent were irrigated with gravity-flow irrigation. Pressure-sprinkler irrigation, by 2003, had captured nearly 60 percent of the area irrigated in the West, and by which time, total irrigated acres had expanded by nearly a million acres while total agricultural water use declined by nearly 800,000 acre-feet.

Tables 1 and 2 also reveal a shift in the type of irrigation technology used across western irrigated agriculture. FRIS information indicates that more recently (since 1994) irrigation technology transitions in the West have shifted, with more emphasis on technology transitions occurring from acreage using improved gravity-flow systems (e.g., furrow systems using piped or lined open ditch field water delivery) to acreage using more conserving pressure-sprinkler irrigation systems (low-pressure sprinkler, LEPA, and drip/trickle systems). Between 1994 and 1998, results show that adoption of improved gravity-flow systems continued to increase for each of the conserving-gravity irrigation definitions (Table 1). For the broadest conserving definition (GRV-3), improved gravity-irrigated acreage increased from 40.0 to 52.0 percent of all gravity-flow irrigated acres. During the same time period, improved pressure-sprinkler irrigation

[3] Data on conserving gravity and conserving pressure-sprinkler systems were inadequate to formulate consistent definitions of conserving irrigation for the 1984 and 1988 FRIS surveys.

increased from 58.0 to 78.0 percent of all pressure-sprinkler irrigated acres. However, from 1998 to 2003, the share of gravity-flow irrigated acres using improved gravity irrigation systems declined for each of the conserving-gravity definitions; for the broadest conserving definition (GRV-3), improved gravity irrigated acreage declined from 52.0 to 41.0 percent. Consistently, improved pressure-sprinkler irrigated acres also continued to increase, although at a slower rate than in the earlier period. Table 2 results, identifying relative shares in water-use by conserving technology definition over time, illustrate a similar shift in recent technology transitions across western irrigated agriculture.

From a policy perspective, these shifts are likely important, in that, a slowing of the transition from conventional gravity-flow irrigation to improved pressure-sprinkler irrigation, may be attributable to some threshold beyond which conservation policy incentives may be less effective (particularly as relates to transitions from conventional gravity to improved pressure-sprinkler irrigation). While Tables 1 and 2 represent westwide statistics, similar patterns exist across western regions (not shown here due to paper length restrictions), but they do vary in relative degree across regions depending upon primary water sources, crop types, and other agro-climatic factors.

Table 3 results show that for gravity irrigation, and for irrigated agriculture in general across the West, producers continue to make much heavier use of conventional infield water-management practices. For gravity irrigation, producers tend to give more emphasis to such conventional practices as reducing irrigation set times, irrigating only alternate furrows (for row crops), and using end-of-field dikes to restrict field runoff. Other, more conserving gravity-flow management practices have either declined in use, or have received little producer attention. Use of tailwater pits to enhance onfarm water reuse (and thereby reduce the need for additional withdrawals) has declined across gravity irrigation, from a high of 22.0 percent in 1994 to 8.0 percent in 2003. Use of laser-leveled acres for gravity irrigation has declined from a high of 27.0 percent in 1998 to 16.0 percent in 2003. In addition, by 2003, other conserving gravity-management practices, such as the use of special furrowing techniques, shortened furrow lengths, and polyacrylamide (PAM), represent a relatively small portion of present-day westwide gravity irrigated agriculture.

Table 3 results also show that despite technological advances in crop/soil moisture sensing, irrigated crop producers in the West continue to depend heavily on the use of more conventional methods in deciding when to irrigate a crop, and by how much. Most producers generally irrigate based on the visible "condition of the crop," or by "feeling the soil" (for its moisture content), or irrigation may be tied to an irrigation calendar schedule or simply whenever water is delivered "in-turn" to the farm. Fewer than 8.0 percent of irrigators throughout the West use soil- or plant-moisture sensing devices or commercial irrigation scheduling services. Fewer than 2.0 percent of producers use computer-based simulation models designed to evaluate crop irrigation requirements based on crop growth-stage consumptive-use needs given local weather conditions.

Given that climate change forecasts predict both significant reductions in future water supply resources, and increases in evaporation and crop evapo-transpiration requirements in much of the western U.S., infield water-management intensity will become significantly more important. As the transition to higher-efficiency physical systems wanes, there may be greater policy emphasis on water management intensity to achieve Federal/State conservation policy goals for a sustainable irrigated agricultural sector in the West.

Summary and Conclusions

In the past 25 years, irrigated agriculture in the West has made significant strides toward a more sustainable future. However, continued concerns over traditional non-agricultural water demands (associated with expected growth from municipal, industrial, environmental, and Native American water-right claims) are compounded by new water demands, specifically, demands induced through climate change and a growing bio-fuel energy sector. These emerging demands will increase pressures on the present allocation mechanism for an increasingly scarce resource, raising uncertainty about the sustainability of irrigated agriculture in the West. Climate change, likely to have the more dominant impact in many areas, raises policy questions about the factors affecting producer adoption of conserving irrigation production systems (including conserving physical systems as well as conserving infield water-management practices), and how western irrigated agriculture will achieve a sustainable future.

Because climate change, via warming temperatures, is expected to not only reduce the quantity and timing of water supplies, but to increase evaporation and crop evapo-transpiration requirements, onfarm water-management will likely become much more critical to a sustainable future for irrigated agriculture in the West. Therefore, understanding producer irrigation technology adoption decisions, their policy implications, and their contribution to a sustainable future for western agriculture, means that policy analysis will need to emphasize transitions in irrigation production systems; that is, analysis that considers producer adoption behavior for both physical systems as well as for onfarm resource-management practices.

For this project, we have specified two models to evaluate technology adoption decisions in the irrigated agriculture sector. First, we adapted the generalized, cost-function based acreage allocation model by Schaible et al. (2009), an extension of the dual approach established by Kim et al. (2005), to evaluate producer production-system technology adoption decisions for surface-water irrigated agriculture in the West. Second, because of the dynamic relationship between groundwater withdrawals and aquifer impacts, and the need for groundwater irrigators to consider resource opportunity costs associated with a common-pool property, we develop a new analytic framework that endogenizes a technology-specific acreage allocation function incorporating onfarm water management within the traditional dynamic-optimization framework for groundwater irrigated agriculture.

For both models, broadening the technology response to incorporate onfarm water management expands the producer technology choice set beyond traditional model definitions. Model estimation results will significantly improve measures of producer behavioral response as well as welfare measures associated with policy simulations of shifting water-supply conditions due to drought, climate change, and emerging water demands throughout the West.

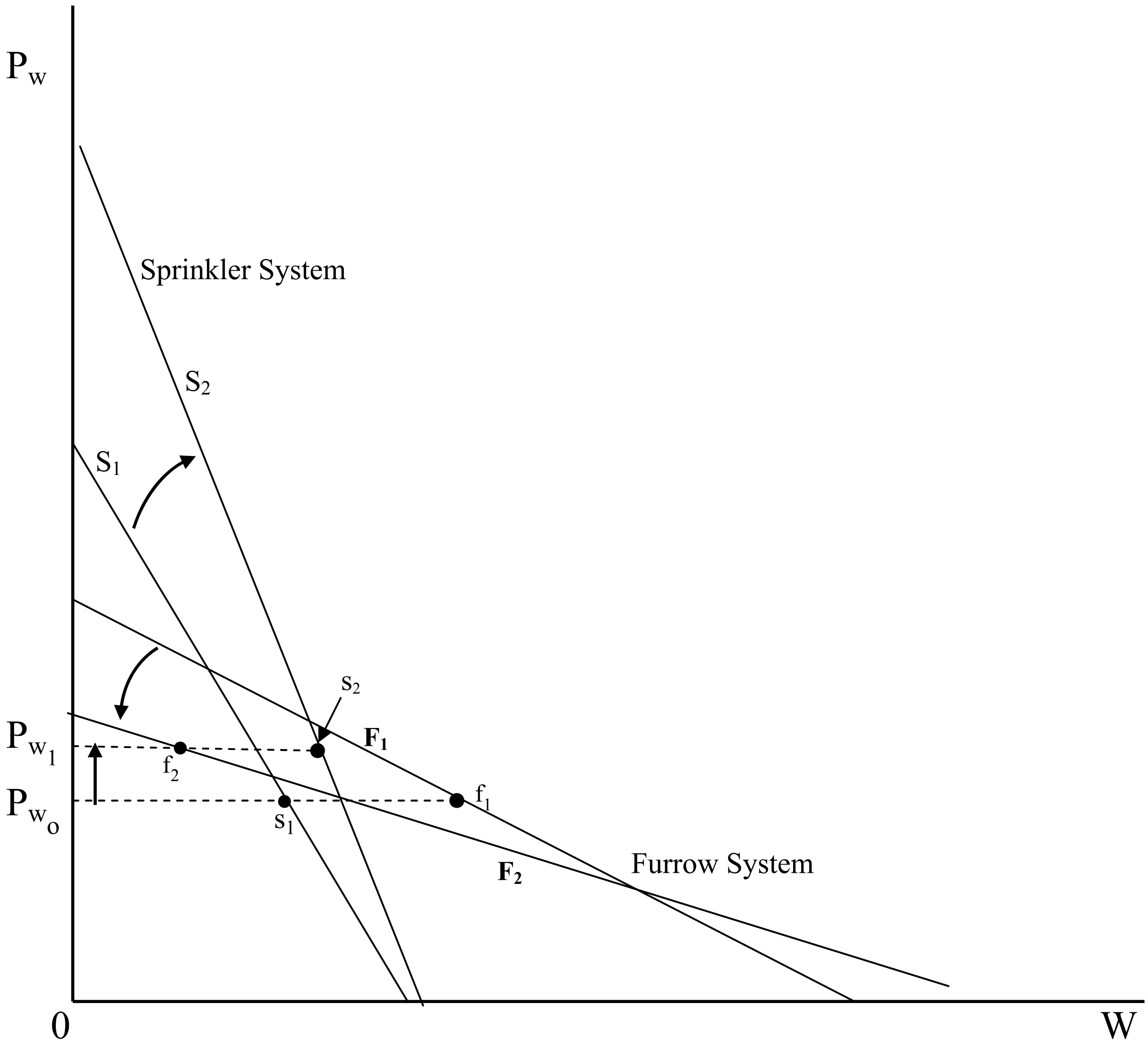

Figure 1. Water Demand Changes Due to Acreage Technology Shifts.

Table 1. Irrigated Acres for the 17 Western States by Alternative Conserving Irrigation Definition: FRIS Data (1984 – 2003)

	Irrigated Acres	Gravity as a % of Tot. Farm Irr. Ac.	Spkr. & Drip/Tr as a % of Tot. Farm Irr. Ac.	Irrigated Acres by Conserving Irrigation Definition [Acres and Percent (%)] For: Conserving Definition 1 [a]	Conserving Definition 2 [a]	Conserving Definition 3 [a]
1984:						
Total Farm Irrigated Acres	39,097,612					
Total Gravity Irrigated Acres	24,084,966	62.0				
Total Pressure (Sprinkler & Drip/Trickle) Irrigated Acres:	14,657,800		37.0			
Conserving Gravity Irrigation (Acres):				NA [b]	NA	NA
(% of Total Gravity Irr. Acres)						
Conserving Pressure Irrigation (Acres):				NA	NA	NA
(% of Total Pressure Irr. Acres)						
1988:						
Total Farm Irrigated Acres	37,996,825					
Total Gravity Irrigated Acres	22,731,136	60.0				
Total Pressure (Sprinkler & Drip/Trickle) Irrigated Acres:	14,991,394		39.0			
Conserving Gravity Irrigation (Acres):				NA	NA	NA
(% of Total Gravity Irr. Acres)						
Conserving Pressure Irrigation (Acres):				NA	NA	NA
(% of Total Pressure Irr. Acres)						
1994:						
Total Farm Irrigated Acres	38,958,806					
Total Gravity Irrigated Acres	20,344,444	52.0				
Total Pressure (Sprinkler & Drip/Trickle) Irrigated Acres:	18,500,862		47.0			
Conserving Gravity Irrigation (Acres):				7,569,428	8,226,094	8,239,126
(% of Total Gravity Irr. Acres)				37.0	40.0	40.0
Conserving Pressure Irrigation (Acres):				1,082,603	6,009,732	10,673,081
(% of Total Pressure Irr. Acres)				6.0	32.0	58.0
1998:						
Total Farm Irrigated Acres	39,049,840					
Total Gravity Irrigated Acres	19,164,703	49.0				
Total Pressure (Sprinkler & Drip/Trickle) Irrigated Acres:	19,664,875		50.0			
Conserving Gravity Irrigation (Acres):				7,757,830	9,836,685	9,888,122
(% of Total Gravity Irr. Acres)				40.0	51.0	52.0
Conserving Pressure Irrigation (Acres):				1,193,636	9,084,497	15,332,970
(% of Total Pressure Irr. Acres)				6.0	46.0	78.0
2003:						
Total Farm Irrigated Acres	39,932,337					
Total Gravity Irrigated Acres	16,491,380	41.0				
Total Pressure (Sprinkler & Drip/Trickle) Irrigated Acres:	23,354,769		58.0			
Conserving Gravity Irrigation (Acres):				5,738,431	6,714,452	6,732,265
(% of Total Gravity Irr. Acres)				35.0	41.0	41.0
Conserving Pressure Irrigation (Acres):				1,765,539	10,399,423	18,450,344
(% of Total Pressure Irr. Acres)				8.0	45.0	79.0

Source: Farm & Ranch Irrigation Surveys (1984, 1988, 1994, 1998, and 2003), National Agricultural Statistics Service, USDA, Washington, DC.

[a] See the text for the three separate definitions for conserving gravity and pressure (sprinkler and drip/trickle) irrigation.

[b] NA = Not Available. (Early FRIS surveys did not collect sufficient data to summarize acres by conserving gravity and sprinkler irrigation groups.)

Table 2. Water Use for the 17 Western States by Alternative Conserving Irrigation Definition: FRIS Data (1984 – 2003)

	Water Use (Acre Feet)	Gravity Irr. as a % of Tot. Farm Wat. Use	Spkr. & Drip/Tr as a % of Tot. Farm Wat. Use	Water Use by Conserving Irrigation Definition [Acre Feet and Percent (%)] For:		
				Conserving Definition 1 [a]	Conserving Definition 2 [a]	Conserving Definition 3 [a]
1984:						
For Total Farm Irrigation	74,274,390					
For Total Gravity Irrigation	52,986,925	71.0				
For Total Pressure (Sprinkler & Drip/Trickle) Irrigation:	20,972,520		28.0			
For Conserving Gravity Irrigation (Ac.Ft.):				NA [b]	NA	NA
(**%** of Total Water for Gravity Irr.)						
Conserving Pressure Irrigation (Ac.Ft.):				NA	NA	NA
(**%** of Total Water for Pressure Irr.)						
1988:						
For Total Farm Irrigation	72,887,539					
For Total Gravity Irrigation	50,008,499	69.0				
For Total Pressure (Sprinkler & Drip/Trickle) Irrigation:	22,704,890		31.0			
For Conserving Gravity Irrigation (Ac.Ft.):				NA	NA	NA
(**%** of Total Water for Gravity Irr.)						
Conserving Pressure Irrigation (Ac.Ft.):				NA	NA	NA
(**%** of Total Water for Pressure Irr.)						
1994:						
For Total Farm Irrigation	70,487,278					
For Total Gravity Irrigation	45,140,601	64.0				
For Total Pressure (Sprinkler & Drip/Trickle) Irrigation:	25,247,291		36.0			
For Conserving Gravity Irrigation (Ac.Ft.):				11,977,815	13,685,132	13,751,255
(**%** of Total Water for Gravity Irr.)				27.0	30.0	30.0
Conserving Pressure Irrigation (Ac.Ft.):				2,605,233	9,447,041	15,994,460
(**%** of Total Water for Pressure Irr.)				10.0	37.0	63.0
1998:						
For Total Farm Irrigation	76,183,611					
For Total Gravity Irrigation	45,520,419	60.0				
For Total Pressure (Sprinkler & Drip/Trickle) Irrigation:	30,076,454		39.0			
For Conserving Gravity Irrigation (Ac.Ft.):				14,546,833	20,204,447	20,311,466
(**%** of Total Water for Gravity Irr.)				32.0	44.0	45.0
Conserving Pressure Irrigation (Ac.Ft.):				3,034,801	15,048,799	24,586,739
(**%** of Total Water for Pressure Irr.)				10.0	50.0	82.0
2003:						
For Total Farm Irrigation	73,593,124					
For Total Gravity Irrigation	37,892,651	51.0				
For Total Pressure (Sprinkler & Drip/Trickle) Irrigation:	35,700,473		49.0			
For Conserving Gravity Irrigation (Ac.Ft.):				10,777,431	13,392,802	13,435,758
(**%** of Total Water for Gravity Irr.)				28.0	35.0	35.0
Conserving Pressure Irrigation (Ac.Ft.):				4,166,792	17,146,002	29,446,291
(**%** of Total Water for Pressure Irr.)				12.0	48.0	82.0

Source: Farm & Ranch Irrigation Surveys (1984, 1988, 1994, 1998, and 2003), National Agricultural Statistics Service, USDA, Washington, DC.

[a] See the text for the three separate definitions for conserving gravity and pressure (sprinkler and drip/trickle) irrigation.

[b] NA=Not Available. (Early FRIS surveys did not collect sufficient data to summarize water use by conserving gravity and sprinkler irrigation groups.)

Table 3. Use of Water Management Practices for the 17 Western States, Across FRIS Survey Years

	1984	1988	1994	1998	2003
Total number of irrigated farms (farms):	179,473	180,525	149,351	147,090	174,936
Total gravity irrigated acres (acres):	24,084,966	22,731,136	20,344,444	19,164,703	16,491,380
Methods Used in Deciding When to Irrigate:					
	Percent (%) of Irrigated Farms				
Use of any method (use of one or more of the decision methods below):	96.0	94.0	96.0	99.0	100.0
Condition of the crop	26.0	69.0	66.0	70.0	77.0
Feel of the soil	40.0	36.0	37.0	40.0	34.0
Use of soil moisture sensing devices	8.0	8.0	9.0	8.0	7.0
Use of commercial scheduling services	3.0	5.0	3.0	4.0	7.0
Use of media reports	4.0	4.0	3.0	5.0	8.0
Based on the schedule of water delivery to the farm	13.0	13.0	18.0	12.0	15.0
Based on a calendar schedule	18.0	18.0	20.0	20.0	21.0
Use of computer simulation models	NA	NA	3.0	1.0	1.0
Use of plant moisture sensing devices	NA	NA	NA	NA	2.0
Irrigate when the neighbors begin to irrigate	NA	NA	NA	NA	7.0
Water Management Practices Used with Gravity-Flow Irrigation Systems:					
	Percent (%) of Gravity Irrigated Acres				
Tailwater pits	NA	20.0	22.0	12.0	8.0
Surgeflow/cablegation irrigation	NA	5.0	4.0	4.0	2.0
Special furrowing techniques	NA	12.0	12.0	6.0	6.0
Shortening of the furrow length	NA	NA	5.0	3.0	3.0
Reducing irrigation set times	NA	NA	13.0	13.0	15.0
Using alternate row irrigations	NA	NA	17.0	15.0	12.0
Use of Polyacrylamide (PAM)	NA	NA	NA	2.0	2.0
Restricting runoff by diking end of field	NA	NA	NA	NA	13.0
Use of mulch or other type of row cover	NA	NA	NA	NA	1.0
Laser-leveled acres	NA	10.0	21.0	27.0	16.0

Source: Farm & Ranch Irrigation Surveys (1984, 1988, 1994, 1998, and 2003), National Agricultural Statistics Service, USDA, Washington, DC.
NA = Not Available. (Early FRIS surveys did not collect data for these decision methods, or water-management practices.)

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