Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 137, Pages 40-46, September 2007

Irrigation Technology and Water Conservation in the High Plains Aquifer Region

Sreedhar Upendram and Jeffrey M. Peterson

Kansas State University

In terms of spatial scale, the decline of the High Plains aquifer is perhaps the largest single water management concern in the United States. The aquifer underlies some 173,000 square miles (Zwingle 1993) spanning portions of the eight states of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. In most of this region, the aquifer is the primary water source for irrigation, household, and municipal uses, with irrigation being the largest use representing over 85 percent of annual withdrawals (U. S. Geological Survey 1995). Ever since irrigation became widespread in the latter half of the twentieth century, the aquifer has been overdrafted and the water in storage has been in a steady state of decline. As much as 40 percent of pre-development storage has been depleted in the most agriculture-intensive areas of the aquifer (Feng and Seggara 1992).

A common policy prescription to conserve ground water and reduce the rate of decline is the provision of subsidies for more efficient irrigation technologies (Johnson et al. 2001). This policy has been implemented in the High Plains region at both the state and federal levels. One such policy administered by the state of Kansas is a cost share program that pays a portion of an irrigator's investment to upgrade technology on an irrigated field – for example by switching from a flood system to a center pivot system (Golden and Peterson 2006). Since the 2002 Farm Act, the federal Environmental Quality Incentives Program includes cost share contracts for water conservation that can be used to subsidize technology upgrades.

Although more modern irrigation technologies are known to improve farmers' profits and reduce production risk (Earls and Bernardo 1992, DeLano and Williams 1997, O'Brien et al. 2000, Peterson and Ding 2005), some have questioned whether they in fact reduce consumptive water use. Several authors have shown that, under certain conditions, farmers with a more efficient irrigation system have an incentive to increase consumptive use (Huffaker and Whittlesey 1995, 2003, Whittlesey 2003) either by expanding irrigated acreage, or increasing net irrigation per acre with a more water intensive crop.

In this paper, we conduct a series of detailed simulations of irrigated crop production in the Kansas High Plains to assess the impact of irrigation technology on water use. We compare the water use, irrigation efficiency, and economic performance of common production scenarios under both technologies. The simulations account for the timing of irrigation and weather events during the growing season as well as the variability of weather conditions across years. Our performance measures reflect averages over a 37-year period of observed weather in the study region. The crop production scenarios differ by irrigated acreage and the irrigated crop choice to highlight the effect of these factors on overall water use.

Concepts and Definitions

Figure 1 illustrates the inflows and outflows of water at the field-level during a single production cycle, the relationships at the core of our analysis. Inflows to the crop root zone consist of effective precipitation, *P*, and gross water applied as irrigation, *GWA*. For our purposes, *GWA* is defined as the amount of water that is pumped from the aquifer and exits the irrigation delivery system.

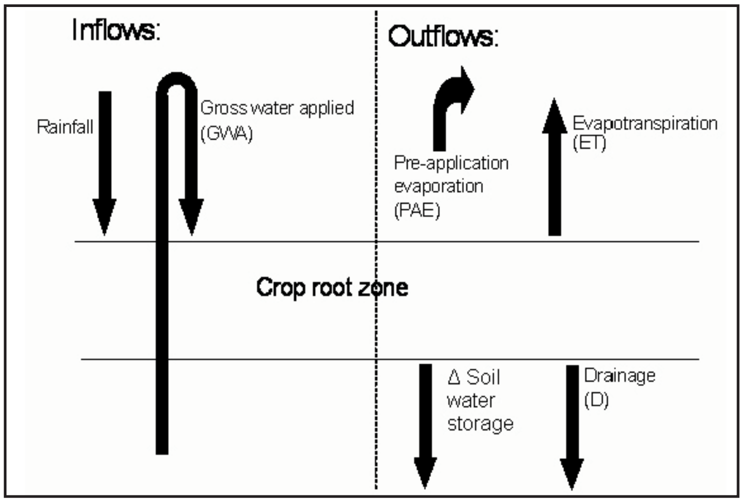

Figure 1. Field-level water inflows and outflows.

Outflows at the field level come in four forms. Pre-application evaporation, *PAE*, is the amount of water returned to the atmosphere after it exits the delivery system but before it reaches the soil or plant surface. Evapotranspiration, *ET*, is the combined amount of water transpired through the crop and evaporated from the soil surface (Scherer et al. 1999); *ET* is also called 'beneficial use,' as it is the portion of outflows generating economic benefits to the irrigator. The third outflow is drainage, *D*, or the amount of water percolating below the crop root zone. Finally, the above inflows and outflows during the year may result in a change in the water stored in the soil, ΔSW.

The outflows can be grouped into two categories. *ET* and *PAE* both represent water irretrievably lost or "consumed" during the growing cycle, and are thus the two components of *consumptive use*. ΔSW and *D* together constitute the return flow to the system, as they are potentially reusable quantities of water in the future. ΔSW is usable in the next growing season while *D* percolates back to the aquifer and can be pumped to the surface again at a later time.[1] By the law of the conservation of matter, inflows must equal outflows. The variables in Figure 1 therefore are related by the equation

$$P + GWA = ET + PAE + D + \Delta SW, \qquad (1)$$

where consumptive use is $ET + PAE$ and return flow is $D + \Delta SW$. Consumptive use is a quantity of interest to water managers because it measures the net draw on the water resource.

A commonly reported measure to compare irrigation technologies is *season-long irrigation efficiency*, denoted *SIE*. *SIE* is directly related to the inflow and outflow measures above. It is defined as

$$SIE = \frac{ET}{P + GWA}. \qquad (2)$$

That is, *SIE* can be interpreted as the share of inflows that are beneficially used. This measure allows consistency in comparison between technologies based on potential reductions in ground water pumped. An improvement in *SIE* has been used as one justification for cost sharing of new technology. For example, in the Kansas cost share program, all contracts include a section that calculates an estimated improvement in irrigation efficiency due to the technology conversion. However, as noted above, an improvement in *SIE* does not necessarily translate to a reduction in consumptive use. The goal of the analysis below is to identify the situations when more efficient systems in fact reduce ground water consumption.

Simulations of Irrigated Production in Western Kansas

Our simulations assess the changes in water use from converting a flood system to a center pivot sprinkler system on a typical irrigated field in western Kansas. Many irrigators made this conversion in the past few decades (Peterson and Bernardo 2003), several of whom received cost share funds from state or federal programs (Golden and Peterson 2006). The field we model is a 160-acre square quarter section, part or all of which is planted to an irrigated crop with the remainder to a non-irrigated wheat-fallow rotation.

In the initial situation when the field is flood irrigated, it is assumed to be irrigated in its entirety (160 acres), or else split into equal irrigated and non-irrigated portions. Based on typical management practices in Kansas, four inches of irrigation water are applied at each event, and events occur as frequently as possible given the delivery capacity of the ground water well. 5 percent of applied water is assumed to be lost to *PAE* (Rogers et al. 1997), while other outflows are computed in the simulation model.

After an upgrade to a center-pivot system, irrigated acreage is fixed at 126 acres, the area of a circle circumscribed in a 160-acre square. Each irrigation event is applied by a single revolution of the pivot arm, and an application of 1 inch per event is assumed. Again conforming to management conventions in the region, irrigation events are assumed to occur as frequently as possible given the pumping capacity. Fifteen percent of applied water is assumed to be lost as *PAE* (Rogers et al. 1997).

Our simulations consider two irrigated crops commonly grown in the region. Corn is a water-intensive crop that is highly sensitive to water stress at critical stages of the growing season. Grain sorghum is a less water intensive alternative, often grown in limited irrigation scenarios, and is less sensitive to the timing of water stress. Six combinations of crops and technologies were modeled in all (Table 1).

Irrigation water for the field is assumed to be supplied from a single well with a pumping capacity of 400 gallons per minute. This represents a moderate to low well capacity in western Kansas, and reflects a "limited irrigation" situation in which crop yield is sensitive to changes in irrigation amounts. Reduced irrigated acreage implies the well can deliver irrigation events more frequently, translating into higher yields per irrigated acre. The bottom row of Table 1 shows the minimum irrigation frequencies in the different scenarios.

We employed a daily-loop agronomic simulator known as the Kansas Water Budget (KWB) model (Stone et al. 1995) to simulate crop production and water use. The KWB model requires daily inputs of weather data (precipitation, maximum and minimum temperatures, and solar radiation) and irrigation water, and from this information calculates daily values of ET, D, and ΔSW. The KWB model aggregates these values for the season and also produces an estimate of crop yield based on accumulated ET during different crop growth stages (Stone et al. 1995). From the estimated yield, we could also estimate net economic return per acre, using price and cost information from Kansas State University Extension crop budgets (Dumler and Thompson 2006a-d).

Simulations were conducted for each scenario in Table 1, for observed daily weather conditions at

Table 1. Crop-technology scenarios.

	Scenario					
Item	F80-C	F160-C	CP-C	F80-S	F160-S	CP-S
Irrigation system	Flood	Flood	Center-pivot	Flood	Flood	Center-pivot
Acreage allocation (acres)						
Irrigated corn	80	160	126	0	0	0
Irrigated grain sorghum	0	0	0	80	160	126
Nonirrigated wheat	80	0	34	80	0	34
Minimum irrigation frequency[a]	16	32	7	16	32	7

a. Defined as the minimum number of days required to apply a single irrigation event on the irrigated portion of the field, assuming that flood systems apply 4 inches per event and center pivot systems apply 1 inch per event.

Tribune, Kansas over the 37 year period 1977-2003. To run the simulations, irrigation schedules were developed using the minimum frequencies in Table 1 and assumed start and end dates of the irrigation season.[2] The KWB model was then executed for each weather year and the yield, water flows, and net returns were recorded for each run. The results were then averaged across years to allow for long-run comparisons of different production scenarios.

Results

Results of the simulations are reported in Table 2. To make consistent comparisons, the water inflows and outflows were aggregated to the parcel level; the values in the first two blocks are field-level measures in acre feet per year. Following the convention in irrigation research, the *SIE* measure is computed by equation (2) for a representative irrigated acre in each scenario over the crop growing season (May 15 – September 21). Net returns are computed for the field as a whole as well as on a per-irrigated-acre basis.

As expected, simulated irrigation efficiencies were higher in the center pivot scenarios than in the flood scenarios, but the efficiency advantage depends importantly on flood irrigated acreage. For both crops, the CP scenario has an efficiency advantage of more than 25 percent compared to the F80 scenario, but an advantage of only 2 percent over the F160 scenario. This is because of a higher frequency of irrigation when only half the field is irrigated (Table 1), which results in much higher drainage losses. Irrigation efficiencies are also higher for corn than sorghum, reflecting corn's superior ability to extract soil water.

Do these efficiency improvements reduce consumptive use? Not necessarily. Holding the crop constant, a conversion from a F80 to a center pivot system will actually increase consumptive use at the field level, despite the dramatic increase in irrigation efficiency. On the other hand, if the farmer

Table 2. Simulated irrigation and economic performance measures.

Item	F80-C	F160-C	CP-C	F80-S	F160-S	CP-S
Inflows (acre-feet)						
Precipitation (P)	227	227	227	227	227	227
Gross water applied (GWA)	160	160	126	160	160	126
Total inflows	387	387	353	387	387	353
Outflows (acre-feet)						
Consumptive Use	314	347	340	300	337	330
Evapotranspiration (ET)	306	339	321	292	329	312
Pre-application evap. (PAE)	8	8	19	8	8	19
Return Flow	73	40	13	77	50	22
Drainage (D)	59	13	10	63	21	18
Change in Soil Water (ΔSW)	14	27	3	14	30	5
Total outflows	387	387	353	387	387	353
Season-long irrigation eff. (SIE)	0.67	0.92	0.94	0.57	0.81	0.83
Net returns ($/irrigated acre)						
Mean	271	181	222	184	173	188
Standard Deviation	14	86	87	8	37	33
Maximum	288	274	317	193	207	219
Minimum	229	-48	-12	157	66	91
Field-level net returns, mean ($)	25,239	28,882	28,565	16,135	27,605	24,307

reduces irrigated acreage from 160 to 126 acres in making the conversion, and again assuming the crop does not change, then consumptive use would fall. The reduction is rather modest, however (7 acre feet or about 2 percent of initial consumptive use), and of course a reduction in consumptive use is to be expected as irrigated area declines.

To make a consistent comparison across the different scenarios, it is appropriate to compare the CP scenario to a flood scenario with the same irrigated acreage. This comparison is illustrated in Figure 2, where the dashed lines interpolate flood consumptive use for acreages between 80 and 160. For both crops, the CP consumptive use lies above the dashed line. This implies that the change in consumptive use due to a conversion from F160 (F80) to CP is disproportionately small (large) compared to the change in irrigated acreage. Put differently, holding the crop and irrigated acreage constant, center pivot systems consume more water.

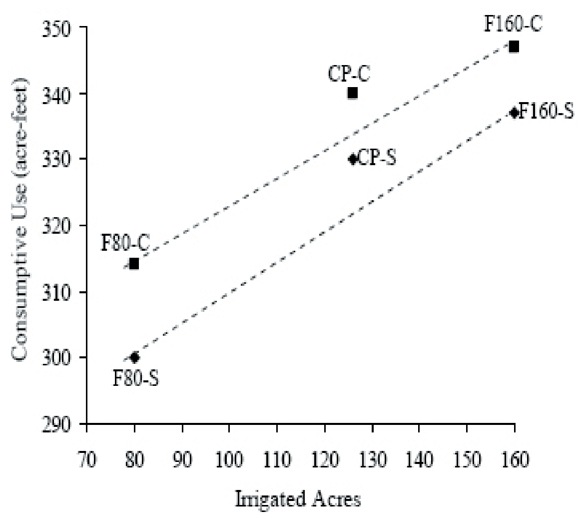

Figure 2. Scatter plot of consumptive use and irrigated acreage.

Of course, the crop and acreage often are not held constant in actual conversions. The economic performance measures in Table 1 provide some insight about the likely crop/acreage choices under the two irrigation systems. Under the flood irrigation system, farmers would earn the highest average net returns ($28,882) by planting corn to the entire 160 acres. However, this alternative is the most risky of all the flood alternatives, with a standard deviation of $86 per irrigated acre and negative returns earned in some years. Farmers could reduce risk substantially with only a modest reduction in average income by planting the 160 acres to sorghum instead. Further reductions in risk (at the cost of successively higher reductions in net returns) could be achieved under the F80-C and F80-S scenarios. However, the risk measures (standard deviation and ranges) in Table 1 represent the irrigated acreage only, and do not account for the additional risk the farmer would bear on the 80 non-irrigated acres. Although the final selection would depend on the farmer's risk tolerance, these results suggest that F160-S is a likely starting point, with only the most risk-tolerant producers choosing F160-C.

Following the conversion to a center pivot system, the CP-C scenario has a substantial advantage in average net returns over CP-S (a difference of about $4,250 or 18 percent), although the the sorghum scenario generates less risk. CP-S would appear to be an unlikely choice, however, as the F160-S scenario has substantially higher mean net returns than CP-S with only slightly higher risk.[3] Taken together, the net return information suggests a typical conversion would be from F160-S to CP-C, resulting in an efficiency increase of 13 percent and a slight increase in consumptive use of 3 acre feet (less than a 1 percent change). Conversions from F160-C to CP-C, which are plausible for risk-tolerant producers, would result in an efficiency gain of 2 percent and a reduction in consumptive use of 10 acre feet (about a 3 percent change).

Thus, under the modeling assumptions made here, the likely changes in crop and irrigated acreage would result in only a slight change in consumptive use following a technology upgrade. In the most favorable case for water conservation, the conversion would achieve a savings of at most 10 acre feet or about three-fourths of an inch per irrigated acre per year. However, an increase in consumptive use is not unlikely.

Conclusions

This article has evaluated the link between improvements in irrigation efficiency and consumptive water use, in the context of irrigated crop production in the U.S. High Plains. Care was taken to account for several details of the irrigated production process, including the scheduling of irrigation and weather events. Overall, we find little evidence of a systematic link between irrigation efficiency and consumptive use. An improvement in irrigation efficiency can result in either more or less water consumption, with the direction of impact depending on the changes in irrigated acreage and crop choice following the efficiency improvement.

Based on the irrigation scenario we model, we find that producers are likely to have an incentive to switch crops from sorghum to corn after replacing their flood system with a more efficient center pivot system. Irrigated acreage is likely to be reduced as well, but the higher water intensity of corn nonetheless causes water use to increase slightly. It is also plausible that farmers grow corn both before and after the technology change, and in this case the improved efficiency will result in less consumptive use. However, the reduction in water use is disproportionately small in comparison to the reduction in irrigated acreage.

Although not found to be economically feasible in this case, in some production settings farmers would increase irrigated acreage when upgrading technologies, creating substantial increases in consumptive use. In a regression analysis of data from annual reports submitted by High Plains irrigators, Golden and Peterson (2006) found that center pivot systems irrigate more acres than flood systems on average, controlling for differences in well capacity, soil conditions, and other spatial factors. On the whole, our findings call into question the policy of conserving water through enhanced irrigation efficiency. If water conservation is the policy goal, the benefits of the substantial public investment in subsidies for new irrigation equipment appear to have been small and may not exist at all. These public funds could be more effectively directed to programs that ensure a reduction in water use, such as the purchase and retirement of water rights. At the same time, there are clearly economic benefits from the improved technology, such as reduced labor costs and more crop revenue per unit of water applied. That many producers in the High Plains have upgraded their technology without subsidies is evidence of these benefits. While there may be legitimate policy reasons for subsidizing new irrigation equipment, water conservation does not appear to be among them.

Acknowledgements

The authors are grateful for financial support for this research provided by United States Department of Agriculture USDA-CSREES Special Grant IT 2002-06188, by the Kansas Water Plan Fund under Kansas Water Office Contract No. 05-118, and by the USDA/ARS Ogallala Aquifer Program.

Author Bios and Contact Information

Sreedhar Upendram is a Graduate Research Assistant and Ph.D. Candidate in the Department of Agricultural Economics at Kansas State University. He received his B.S. degree from Acharya N.G. Ranga Agricultural University, Hyderabad, India and M.S. degree from University of Arkansas, Fayetteville. Contact: sreedhar@agecon.ksu.edu.

Jeffrey M. Peterson is an Associate Professor in the Department of Agricultural Economics at Kansas State University. He conducts research on the interaction between natural resources and the agricultural economy, currently focusing on the economic factors contributing to the decline of the High Plains aquifer, and on market mechanisms for maintaining water quality in agricultural watersheds. He received his B.S. degree from the University of Wisconsin-River Falls and his M.S. and Ph.D. degrees from Cornell University. Contact: jpeters@ksu.edu.

Endnotes

1. However, the speed of the return flow is very slow in general and varies spatially depending on the depth to the aquifer and the geology of the layers above it.
2. The start and end dates were based on typical management practices in western Kansas (Stone 2005). For corn and grain sorghum the irrigation season began on June 15 and ended on September 5.
3. Again, it should be noted that the estimated standard deviation of CP-S, $33 per acre, does not account for the additional risk created by the non-irrigated acreage. Depending on the riskiness of non-irrigated production, which was not estimated in this study because KWB was designed for irrigated crops, it is possible that the overall risk of CP-S is larger than that of F160-S.

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