Great Plains Research: A Journal of Natural and Social Sciences

Great Plains Studies, Center for

1-1-2003

High Plains Regional Aquifer Study Revisited: A 20-Year Retrospective for Western Kansas

Jeffrey Peterson
Kansas State University

Daniel Bernardo
Kansas State University

Peterson, Jeffrey and Bernardo, Daniel, "High Plains Regional Aquifer Study Revisited: A 20-Year Retrospective for Western Kansas" (2003). *Great Plains Research: A Journal of Natural and Social Sciences.* Paper 662.
http://digitalcommons.unl.edu/greatplainsresearch/662

Great Plains Research 13 (Fall 2003): 179-97

HIGH PLAINS REGIONAL AQUIFER STUDY REVISITED: A 20-YEAR RETROSPECTIVE FOR WESTERN KANSAS

Jeffrey M. Peterson and **Daniel J. Bernardo**

Department of Agricultural Economics
Kansas State University
Manhattan, KS 66506
jpeters@agecon.ksu.edu

ABSTRACT—The most comprehensive water policy analysis conducted on the High Plains region to date was the High Plains Ogallala Regional Aquifer Study completed in 1982. Twenty years later, we had a unique opportunity to compare the projections from this study with the changes that actually occurred over the past two decades. Specific comparisons were made for the area of western Kansas overlying the High Plains Aquifer. These comparisons revealed some significant differences in the status of the aquifer and in the region's economic development, relative to the predictions of the study. Most notably, contrary to the study's predictions, irrigated area did not decline precipitously, but rather continued to increase during the period. Despite large increases in irrigated area and production of more water-intensive crops, such as corn and alfalfa, both per-unit area and total water use declined over the 20 years. Differences in observed and projected results can be attributed to a variety of factors, including large differences in crop prices, yield trends, energy prices, farm commodity programs, and irrigation technologies relative to those assumed in the study. Future research will need to better account for these factors to offer useful guidance in setting water management policies.

Key Words: agricultural economy, energy prices, irrigation, Ogallala Aquifer, water policy

Introduction

The Ogallala Aquifer (also known as the High Plains Aquifer) underlies a considerable portion of the Great Plains, particularly in the High Plains of Texas, New Mexico, Oklahoma, Kansas, Colorado, and Nebraska (Schloss et al. 2000). The aquifer covers a total of 451,000 km^2 and has a thickness ranging from less than 0.3 m to 396 m, with an average depth of

61 m (High Plains Study Council 1982). The aquifer serves as the lifeblood of the region's economy, providing the major water source for agricultural, municipal, and industrial development. More than 90% of the water pumped from the Ogallala Aquifer is used for irrigation (Ogallala Aquifer Management Advisory Committee 2001). Principal irrigated crops in the region include cotton, corn, alfalfa, grain sorghum, soybeans, and wheat (USDA-NASS 2002). These crops provide local livestock operations with large amounts of feed and are a principal reason the High Plains is home to one of the largest cattle-feeding and meatpacking complexes in the world (High Plains Study Council 1982).

During the late 1970s and early 1980s, declining water supplies and increasing energy costs prompted considerable interest concerning the sustainability of the High Plains Aquifer (Kansas Water Office 1982b). Irrigation development resulted in a greater than threefold increase in irrigation pumping from 1950 to 1980, and an increase in irrigated area from 1.4 million ha to 5.7 million ha (High Plains Associates 1982; USDA-NASS 1998). Annual water withdrawals from the aquifer had increased from less than 8.6 billion m^3 in 1950 to over 25.9 billion m^3 by 1980 (High Plains Associates 1982). By the late 1970s, annual drawdown of the aquifer exceeded 1 m per year in some regions, and well-pumping capacities were declining at alarming rates (Kansas Water Office 1982b). These circumstances led to several studies addressing the economic impacts of alternative water policies, as well as studies evaluating irrigator response to water-supply shortages (e.g., Ellis et al. 1985; Nieswiadomy 1985; Harris and Mapp 1986).

The most comprehensive water policy analysis conducted on the High Plains region to date was the High Plains Ogallala Regional Aquifer Study (hereafter the High Plains Study), commissioned by the Department of Commerce and the US Congress (High Plains Study Council 1982; High Plains Associates 1982). The enabling legislation charged the Department of Commerce to "study the depletion of natural resources of those regions of the states of Colorado, Kansas, New Mexico, Oklahoma, Texas, and Nebraska presently utilizing the declining water resources of the Ogallala aquifer, and to develop plans to increase water supplies in the area and report thereon to Congress, together will any recommendations for further action" (High Plains Study Council 1982:2). The study was completed in 1982, and its findings served as an important source of guidance for the formation of water policies aimed at sustaining the life of the Ogallala Aquifer.

Now, 20 years later, we had a unique opportunity to compare the projections from the study with the changes that actually occurred over the past two decades. This comparison revealed some significant differences in the status of the aquifer and the region's economic development from those predicted in the High Plains Study. The objective of this paper is to review the study and examine the causes of the somewhat poor performance of the models used to predict both the water resource situation and the economic characteristics of the region. To keep this analysis manageable, we focused on the area of western Kansas overlying the High Plains Aquifer. However, because of the similarity in cropping systems, climate, and water supplies, the general results are applicable to most of the central High Plains, consisting of the northern Texas Panhandle, western Oklahoma, western Kansas, and small portions of Colorado and New Mexico (Bernardo et al. 1993b). This knowledge should prove useful in improving regional models used to assess water conservation policies.

Methods

The history and administration of the High Plains Study is described in its summary report (High Plains Study Council 1982). The governors of the High Plains states organized the High Plains Study Council to guide and direct the study. Private research firms were then commissioned to oversee the project, but the research was independently conducted in each state, most commonly by the land-grant institution.

The principal objectives of the High Plains Study were to (1) compute estimates of the local, state, and national economic and social benefits derived from the resources of the High Plains–Ogallala Aquifer area, (2) project the probable consequences of water resource management alternatives for the High Plains region, and (3) compute estimates of the cost of importing water to the area (High Plains Study Council 1982). Several scenarios were addressed in the study, including a baseline and alternative water-conservation scenarios, involving mandatory and/or voluntary conservation of water, water supply augmentation, and intrastate surface-water allocation transfer. Each scenario was analyzed over a 40-year time horizon, based on annual solutions for 1985, 1990, 2000, and 2020. The baseline scenario represented the closest policy setting to what actually transpired over the past two decades, since strict water use regulations, water supply augmentation, and interregional water transfers represented in the other scenarios did not occur.

The model for Kansas was developed using a linear programming framework to represent the agricultural production sector overlying the High Plains Aquifer (Kansas Water Office 1982a, 1982b). The model was designed to maximize farm returns by selecting the area of irrigated and nonirrigated crops, type of irrigation system, energy source, and amount of water applied per unit area under various production situations. Each production situation was defined by a combination of climate, soil type, and groundwater availability. Irrigated crop alternatives were corn, wheat, grain sorghum, alfalfa, soybeans, and sunflowers. Nonirrigated crops included in the model were wheat and grain sorghum.

The baseline scenario involved no major changes in state water-use regulations. It was assumed that efficiency-augmenting technologies were adopted as they became available. Projections of energy and crop prices were provided to the state researchers by contracted consultants (Kansas Water Office 1982b). Energy prices were expected to rise rapidly in the early stages of the study period (1997-1985) and moderately thereafter. Commodity prices were projected to increase in real terms throughout the 40-year time period. More specifically, wheat, corn, grain sorghum, and soybean prices were expected to increase 20%, 40%, 50%, and 50% in real terms, respectively, over the 40 years. Yields for irrigated corn, soybeans, and sunflowers were projected to increase 40% by 2020, while irrigated wheat and sorghum yields were projected to increase 80% and 50%, respectively. Projected increases for nonirrigated crop yields were 80% for wheat and 90% for grain sorghum. Selected model results from the baseline scenario are reported as "projected" values (Table 1).

To compare the projections with observed outcomes, we compiled data on irrigation patterns for the western third of Kansas from 1977 to 2000. Commodity prices and land areas planted to various crops were taken from the online database maintained by the US Department of Agriculture, National Agricultural Statistics Service (USDA-NASS 2002). To be consistent with the projections from the High Plains Study, all prices and revenue measures were deflated to 1977 dollars using the Consumer Price Index. Water-use and irrigation-system-type data were compiled from the database of annual water-use reports maintained by the Kansas Division of Water Resources. Water-level changes in the Ogallala Aquifer were based on results in Schloss et al. (2000) and Woods et al. (2000). Additional comparisons are reported in Peterson and Bernardo (2003).

TABLE 1

PROJECTED WATER USE, PRODUCTION, AND REVENUE IN WESTERN KANSAS FROM THE HIGH PLAINS STUDY, VS. ACTUAL VALUES

Item	1977	1985	1990	2000	2020
Irrigated area (thousand ha)					
Projected	882	720	441	308	235
Actual	882	894	813	935	—
Nonirrigated area (thousand ha)					
Projected	1,607	2,027	2,214	2,444	2610
Actual	1,607	1,862	1,821	1,712	—
Value of production (million $)					
Projected	657	858	805	936	1,263
Actual	657	891	790	544	—
Total production, corn (thousand tons)					
Projected	2,286	2,426	979	613	538
Actual	2,286	2,031	2,714	6,152	—
Total production, grain sorghum (thousand tons)					
Projected	1,122	1,310	1,472	1,758	2,381
Actual	1,122	2,314	1,332	1,370	—
Total production, wheat (thousand tons)					
Projected	3,767	4,056	4,290	5,202	6,734
Actual	3,767	5,400	5,635	3,490	—
Total production, alfalfa (thousand tons)					
Projected	1,101	1,183	1,418	1,510	1,507
Actual	1,101	1,176	1,163	1,592	—

Sources: Kansas Water Office (1982b) and USDA-NASS (2002).

Results

Projections from the High Plains Study

In the solutions to the programming model for western Kansas (Kansas Water Office 1982b), irrigated land area declined from about 0.9 million ha to 0.3 million ha between 1977 and 2000, while nonirrigated area increased from about 1.6 million ha to over 2.4 million ha. For the most part, irrigated area was converted to nonirrigated production, although about 0.26 million nonirrigated hectares were added during the period that previously had been in fallow. A trend of irrigation abandonment continued through 2020. The most important factors contributing to the decline in irrigated area were water-supply limitations and rising pumping costs resulting from projected increases in energy prices.

From an income perspective, the value of agricultural production in the region increased over the period despite large losses of irrigated area. Both crop yields and real crop prices rose over time; the value of crop production increased from about \$657 million in 1977 to \$936 million by 2000, and to over \$1.2 billion by 2020 (in 1977 dollars). Decreases in the total value of irrigated production were more than offset by a threefold increase in the total value of nonirrigated crop production. In 2000, a total of \$203.5 million was derived from irrigation, and \$731.9 million from nonirrigated production, representing a 39% decrease and a 125% increase from the values in 1977, respectively.

In general, the results of the High Plains study indicated that aquifer depletion would be less severe than previously thought (Kansas Water Office 1982a). As a result of declining irrigated area and increases in application efficiency, water use was projected to decline over the 40-year study period. Total annual water use was estimated to decline from the initial level of 4.35 billion m^3 to 1.25 billion m^3 in 2000, and to 1.02 billion m^3 by 2020. Although the water table had been declining at an average rate of 0.42 m per year from 1969 to 1979 (Woods et al. 2000), the rate of decline was projected to slow over the 40-year study period to a rate of less than 0.3 m per year (Table 2).

Comparison of Projected and Observed Results

We found that the projections from the High Plains Study model grossly overestimated the conversion of irrigated land to nonirrigated production (Table 1). Irrigated land area actually trended up, particularly in the

TABLE 2

PROJECTED SATURATED THICKNESS OF THE AQUIFER (IN METERS) VS. ESTIMATED ACTUALTHICKNESS, BY GROUNDWATER MANAGEMENT DISTRICT

	1977	1985	1990	2000	2020
District 4 (Northwest Kansas)					
Projected	29.1	27.1	26.1	24.6	23.0
Actual	29.1	27.9	27.4	26.8	—
District 1 (West-Central Kansas)					
Projected	16.2	12.1	11.0	10.0	8.0
Actual	16.2	13.6	12.5	11.1	—
District 3 (Southwest Kansas)					
Projected	74.2	66.8	63.4	59.6	55.1
Actual	74.2	69.8	67.4	64.0	—

Note: Saturated thickness is defined as the average distance between the water table and the bedrock floor of the aquifer. Actual levels are estimated based on the average annual rates of decline computed by Schloss et al. (2000). Projected levels are from Kansas Water Office (1982b).

decade of the 1990s, instead of declining significantly. By 2000 the gap between projected and actual irrigated area reached about 650,000 ha. The largest share of this difference was due to irrigated corn, which exceeded projections by about 400,000 ha in 2000. Nonirrigated area remained relatively constant over time, despite projections of a 30% increase from 1977 to 2000.

We also found that the model failed to predict observed changes in the mixture of both irrigated and nonirrigated crops. Over the last decade, an increasing percentage of irrigated area has been planted with water-intensive crops (corn and alfalfa) instead of less-water-demanding alternatives (primarily grain sorghum, wheat, and soybeans). Indeed, the area of the non-water-intensive crops has been falling in absolute terms since 1990 while the area of corn and alfalfa has approximately doubled (USDA-NASS 2002).

As a result of such large discrepancies in forecasting crop area, the region's production of grain and forage crops differed significantly from what was projected in the High Plains Study. This discrepancy was most evident in irrigated corn production, where the actual production in 2000 was tenfold higher than projected (Table 1). Production of wheat and grain sorghum were overestimated, largely due to the large increase in nonirrigated area that was forecasted (Table 1).

Contrary to the positive income predictions in the High Plains Study, the value of crop production fell in real terms between 1977 and 2000 (Table 1). While the total value of crop production was projected to increase to $936 million by 2000, it actually decreased to $544 million (Table 1). This difference is related to changes in the two factors that determine production returns, yield per acre and crop prices. The real prices of major crops were forecasted to rise steadily after 1977 but instead fell dramatically (Fig. 1A). These lower prices were offset somewhat by the fact that crop yields grew steadily, at rates that exceeded expectations (Fig. 1B). Nonetheless, the total value of production occurring during the period had little resemblance to projected values. The distribution of the total value of crop production between irrigated and nonirrigated crops also differed substantially from the projections. In 2000, 21% of the total value of production was projected to be derived from irrigated production, but in reality over 60% could be attributed to irrigation (Peterson and Bernardo 2003).

Declining water levels in the Ogallala Aquifer motivated the High Plains Study as well as much of the research that followed it. As the High Plains Study predicted, the water level has continued to decline since the late 1970s, but at a slowing rate. This pattern occurred in the three groundwater-management districts in western Kansas (Table 2), where the groundwater level is measured as the average saturated thickness of the aquifer throughout each district. In Groundwater Management District 3 in southwest Kansas, the average saturated thickness was projected to decline from 74 m in 1977 to 60 m by 2000. However, based on the average rates of decline published by the Kansas Geological Survey, the actual saturated thickness only decreased to 64 m (Woods et al. 2000). Similar patterns occurred in Groundwater Management Districts 1 and 4, covering west-central and northwest Kansas, respectively (Table 2).

Because the Ogallala recharges very slowly, the rate of water-level decline is directly related to the gross amount of water used (Schloss et al. 2000). Both predicted and actual water use decreased from 1990 to 2000, the period when reliable water-use data are available (Fig. 2). However, the observed trend lies substantially above the projection from the High Plains Study. Actual water use appears to be on a steady downward trend, and

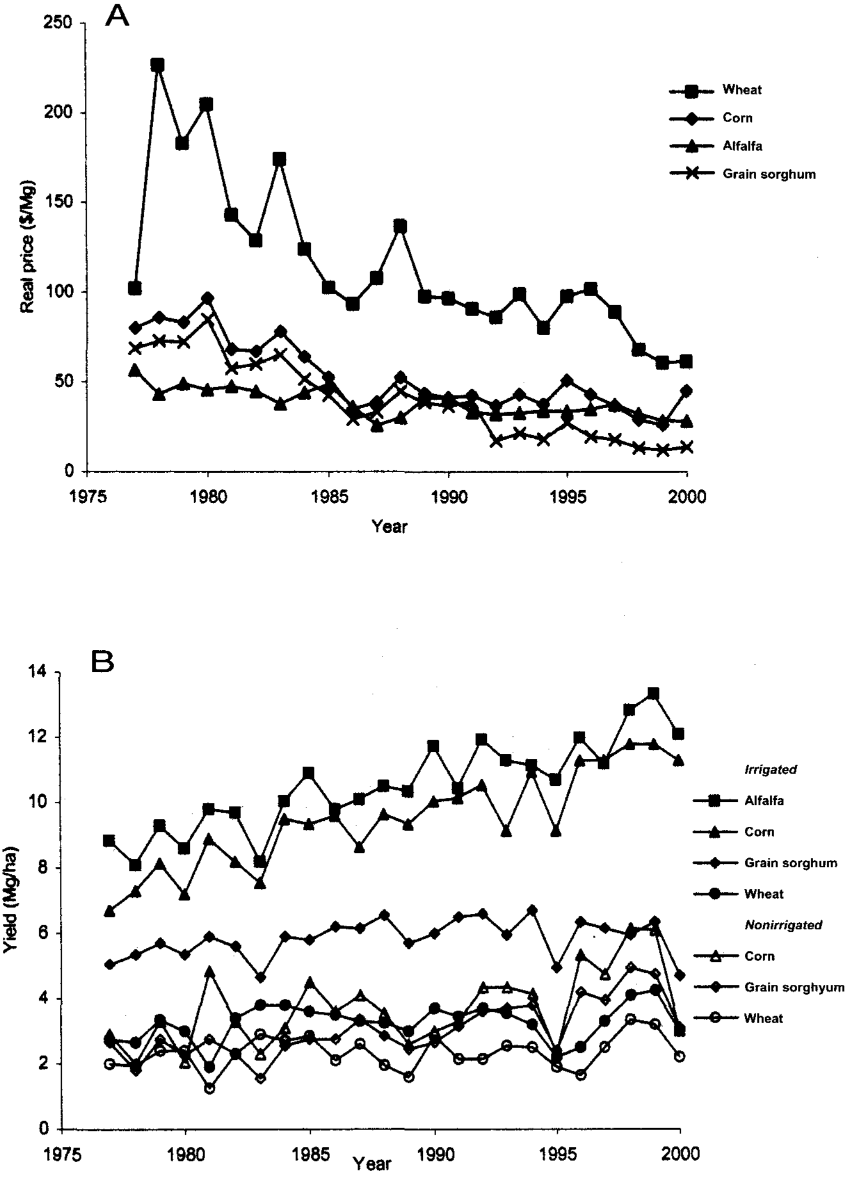

Figure 1. Crop prices (A) and yields (B), western Kansas, 1977-2000. (Source: USDA-NASS 2002.)

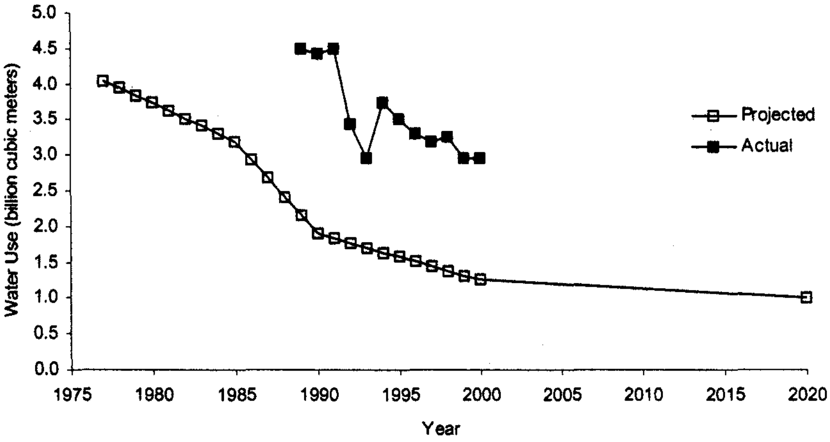

Figure 2. Projected water use in western Kansas from the High Plains Study, vs. actual use from 1990 to 2000. (Sources: Kansas Water Office 1982b; Kansas Division of Water Resources)

much of its variability across years occurs because irrigation is applied to supplement varying amounts of rainfall. This is well illustrated in the significant drop in observed water use during the relatively wet years of 1992 and 1993 (Kansas Water Office 1994).

By definition, total water use is equal to the number of irrigated hectares multiplied by the average application rate per hectare. It is useful to decompose water use into these two more-basic components. The trend in average application rates parallels that of overall water use (Fig. 2). Application rates varied in response to rainfall differences across years, and they exhibited a statistically significant downward trend from about 460 mm in 1990 to 305 mm in 1999 (Peterson and Bernardo 2003). Because overall water use fell (Fig. 2), the decline in application rates evidently more than offset the slow but steady increases in irrigated area after 1990 (Table 1).

A contributing factor to reductions in the application rate was improved irrigation technology, which allows water to be distributed to crops more efficiently. The composition of irrigation systems changed dramatically in western Kansas during the 1990s (Fig. 3). The area irrigated by center-pivot systems rose from about 360,000 ha to 650,000 ha, accounting for more than two-thirds of irrigated area in 2000. Of the center-pivot area in 2000, more than 440,000 ha were irrigated by systems that deliver water at or below the plant canopy (i.e., center pivots with drop tubes), which are

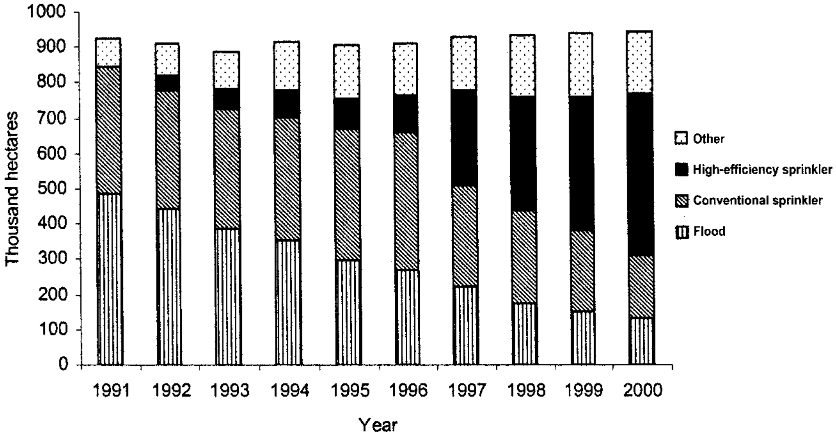

Figure 3. Composition of irrigation-system types, western Kansas, 1991-2000. (Source: Kansas Division of Water Resources)

purported to achieve application efficiencies of over 90%. Meanwhile, the area of inefficient flood irrigation systems has declined from 490,000 ha in 1991 to about 100,000 ha in 2000. The High Plains Study underestimated this conversion from flood to center-pivot irrigation. In addition, the impact of high-efficiency systems was not anticipated. As a result, average application efficiency was projected to increase from 75% to 79.5% from 1977 to 2000, but it actually increased to approximately 83% (USDA-NASS 1998). Since irrigation efficiencies can prolong the usable life of a well, this may partially explain the large underestimation of irrigated cropland in 2000.

Discussion

Several patterns can be discerned from the western Kansas irrigation trends described above. Total irrigated area rose gradually (Table 1), and a rapidly growing share of this area was devoted to water-intensive crops. Nonetheless, both per-unit area and total water use declined (Fig. 2), which may be related to the growing number of efficient irrigation systems (Fig. 3). In general, the policy models developed from the High Plains Study did not perform well in forecasting these trends.

Several factors contributed to the poor performance of the models in projecting actual trends in irrigated area, water use, and farm income. At least five principal factors were involved. First, the revenues from both irrigated and nonirrigated crop production differed significantly from those assumed in the study. Second, real energy costs did not increase as expected. Third, the agricultural policy environment changed dramatically. Fourth, the availability and adoption of water-efficient irrigation technologies was underestimated. Fifth, the hydrology of the Ogallala Aquifer was not modeled accurately. We discuss each of these factors below.

Revenues from Irrigated and Dryland Production

Several factors contributed to the large difference between predicted and actual irrigated crop area. Much of the difference is likely due to assumptions in the model concerning changes in crop revenues over the 20-year period (Table 1). The relevant discrepancy was not in absolute revenue levels, but in the relative levels for irrigated and nonirrigated crops and across various irrigated crops. The revenue trends are the combined outcome of changes in prices and crop yields over time (Fig. 1). Yields of irrigated crops in this region greatly exceeded those of nonirrigated crops over the past 20 years, as expected (Fig. 1B). However, the disproportionate increases in alfalfa and irrigated corn yields were not expected. Varietal improvement and other technological innovations have raised the yields of these crops about twice as fast as any other crop. This change explains the increase in corn area to an all-time high of over 500,000 ha in 2000, in contrast to a projected decline to 80,000 ha (Kansas Water Office 1982b).

The increase in irrigated area has allowed additional production of corn and alfalfa, which supply the region's growing cattle-feeding and dairy industries. Despite the increases in regional feed production, western Kansas remains a net importer of feed grains and alfalfa hay. The High Plains Study did not even consider nonirrigated corn as a production possibility; however, varietal and agronomic improvements resulted in an increase of nonirrigated corn production in excess of 220,000 ha by 2000. The area planted to oilseeds (soybeans and sunflowers) has also increased during this period, particularly in regions of northwest Kansas (USDA-NASS 2002).

Lower Real Energy Costs

Dramatic differences in projected and actual energy prices are another significant factor contributing to the discrepancies in extent and composition of irrigated land area in the region. Following the prediction of energy experts at the time, the High Plains Study predicted a steady rise in future energy costs, which was an important factor driving the projected decrease in irrigated area. By 2000 energy prices were projected to increase 75%, 109%, and 320% for electricity, diesel, and natural gas, respectively (Kansas Water Office 1982b). Instead, energy costs fell in real terms since 1977 (USDOE-EIA 2001), likely supporting the rising trend in irrigated area. Energy prices are also negatively related to the relative profitability of water-intensive crops, because more fuel is consumed to irrigate these crops relative to non-water-intensive crops (Dumler et al. 2002a, 2002b; O'Brien et al. 2002). Buller and Williams (1990) found that the optimal amount of land in corn for a representative farmer would increase in times of relatively low energy prices. Since real energy prices declined over time, water-intensive crops such as corn and alfalfa have become more profitable than was projected by the High Plains Study.

Federal Farm Policies

Farm policy changes have also been a likely contributor to increases in irrigated area and water-intensive crops. Specifically, the federal farm programs established by the Food, Agriculture, Conservation and Trade (FACT) Act, passed in 1990, and the Federal Agriculture Improvement and Reform (FAIR) Act in 1996 both influenced cropping patterns (Lubben 2001). Farm programs in the 1980s required producers to plant in accordance with their "base acres" [Base acres were generally computed as the average number of acres planted (or considered planted) to a crop during the five previous crop years (USDA-ERS 2003)] and often included provisions to restrict the total area under production. The FACT Act eliminated the cross-compliance clause, so that farmers would still be eligible for a crop payment even if their "base acreage" had been exceeded for another crop. The FAIR Act established a set of fixed payments to farmers that were completely decoupled from crop allocation decisions. Since corn and alfalfa became more profitable, this increased flexibility likely supported the trend toward more land in water-intensive crops. For example, Llewelyn et al. (1996) found that the profit-maximizing pattern of crops would contain more land in corn under FAIR than under the FACT policy.

Finally, an increased emphasis on marketing-loan programs also has likely encouraged irrigated production. Under these programs, farmers receive payments equal to actual production multiplied by the difference between the actual price and a predetermined "loan rate" or support price (Westcott and Price 2001). Thus, higher yields of irrigated production lead not only to more revenue through the marketplace but also to increased government payments in times of low prices.

Improved Irrigation Technologies

High-efficiency irrigation technologies have been adopted more rapidly than was predicted by the High Plains Study. In general, subsequent studies evaluating the profitability of irrigation investments were more accurate in projecting changes in technology (e.g., Earls and Bernardo 1992; DeLano et al. 1997; O'Brien et al. 2000). The consensus of these studies predicted movement from flood to center-pivot irrigation and from high-pressure to low-pressure center pivots. More sophisticated systems, such as subsurface drip irrigation, were generally considered nonprofitable investments (Dhuyvetter et al. 1994; O'Brien et al. 1998). Trends in observed irrigation investments (Fig. 3) are consistent with these findings.

Investments in irrigation technology are interrelated with changes in cropping patterns. The link between these factors is a dynamic one in which causality runs in both directions. Water-intensive crops would be more profitable if a farmer already has invested in an efficient technology, since these systems can deliver more water to the crop at critical points in the growing season (Buller et al. 1988; DeLano and Williams 1997). At the same time, farmers might invest in more-efficient systems because the systems would make it feasible to grow water-intensive (but profitable) crops. Ellis et al. (1985) found that irrigation investments could be directly related to the increase in total irrigated area, since more-efficient systems allow limited water supplies to be spread over more hectares. These factors are difficult to represent in large-scale regional models, possibly explaining the limited irrigation investment projected in the High Plains study.

Several other factors also may have contributed to the low projected level of irrigation investment. First, despite projected increases, real costs of new irrigation systems have changed little over the past two decades (Bigge et al. 2002). Second, the reduced labor requirement of sprinkler irrigation was an important factor causing movement from surface to center-pivot systems (O'Brien et al. 2000). Converting to center pivots reduced both operator labor requirements and labor expenses, sometimes eliminating the need to hire irrigator labor.

Inaccurate Hydrologic Modeling

Part of the inaccuracies in the forecasts from the High Plains Study can be traced to the lack of detail in the models, particularly regarding hydrology. For example, one puzzle in comparing the observed patterns to the projections from the High Plains Study was the fact that water levels in the aquifer fell more slowly than projected, even though water use exceeded projections (Table 2, Fig. 2). This anomaly may be explained by the simplistic hydrologic modeling method, which ignored the spatial variability in the aquifer and horizontal flow (Kansas Water Office 1982b). To address the need for more accurate hydrologic predictions, researchers at the US Geological Survey developed MODFLOW, a spatially explicit groundwater model (McDonald and Harbaugh 1988). This model was linked to an economic model for the central High Plains in a more recent study (Bernardo et al. 1993a, 1993b), which predicted water-level changes more accurately over the 1991-2000 period.

Implications for Policy and Future Research

The High Plains Study was conducted in an era of impending water scarcity, rising energy costs, and uncertainty concerning the physical and economic life associated with the Ogallala Aquifer. The regional policy model used in this study identified the links between variables and attempted to predict future changes in irrigated agriculture and water use in a holistic and mutually consistent manner. In retrospect, the predictions for the first half of the 40-year time horizon generally were not accurate. The causes of this inaccuracy were the difficulty in predicting underlying trends in basic factors and the numerous simplifying assumptions needed for the models to be manageable.

As Buller (1988) pointed out, however, evaluating the predictions of models in this way partly misses the point of the modeling effort. Any policy model run using the correct changes in yields and prices undoubtedly would have predicted the water use, irrigated area, and income trends more accurately. The predictions failed not because the researchers failed to understand the forces at work, but because the assumed trends in some basic factors turned out to be incorrect. An important contribution of this research was conceptual, in that it identified the links between irrigation patterns and a set of contributing factors.

To be useful in setting policies, future research must address the limitations of the High Plains Study and studies that followed (e.g., Bernardo et al. 1993a, 1993b; Buller 1996). As water policies that are more divergent from the past situation (e.g., restricting water use to achieve "zero depletion" in the water table) are debated, it will be crucial to better understand and quantify the physical and economic relationships that affect the behavior of agricultural producers. Some of this knowledge has already been acquired over the past 20 years and is summarized in Peterson and Bernardo (2003). More-powerful computing technology has allowed models to become more complex, permitting the use of more detailed and disaggregated data (e.g., Paris 2001). In addition, uncertainty in future trends can be better quantified by modeling a larger number of possible scenarios. Further research is needed to provide more precise guidance in forming policies to sustain the aquifer and the regional economy.

References

Bernardo, D.J., H.P. Mapp, G.J. Sabbagh, S. Geleta, K.B. Watkins, R.L. Elliot, and J.F. Stone. 1993a. Economic and environmental impacts of water quality protection policies: 1. Framework for regional analysis. *Water Resources Research* 29:3069-79.

Bernardo, D.J., H.P. Mapp, G.J. Sabbagh, S. Geleta, K.B. Watkins, R.L. Elliot, and J.F. Stone. 1993b. Economic and environmental impacts of water quality protection policies: 2. Application to the Central High Plains. *Water Resources Research* 29:3081-91.

Bigge, H.M., L.J. Tsoodle, and C.A. Wilson. 2002. Irrigated equipment cost survey in Kansas. Staff Paper 02-03. Department of Agricultural Economics, Kansas State University, Manhattan, KS.

Buller, O.H. 1988. Review of the High Plains Ogallala Aquifer Study and regional irrigation adjustments. Contribution No. 88-576. Kansas Agricultural Experiment Station, Kansas State University, Manhattan, KS.

Buller, O.H. 1996. Economic impact of zero depletion and acre-inch restrictions on irrigated crop production and income in northwest Kansas. Research Report 24. Department of Agricultural Economics, Kansas State University, Manhattan, KS.

Buller, O.H., H.L. Manges, L.R. Stone, and J.R. Williams. 1988. Selecting irrigated crops for net income and water conservation in western Kansas. Report of Progress No. 536. Kansas Agricultural Experiment Station, Kansas State University, Manhattan, KS.

Buller, O.H., and J.R. Williams. 1990. Effects of energy and commodity prices on irrigation in the High Plains. Report of Progress No. 611. Kansas Agricultural Experiment Station, Kansas State University, Manhattan, KS.

DeLano, D.R., and J.R. Williams. 1997. Cost-return projections for corn, grain sorghum, and wheat under alternative irrigation systems. Staff Paper 97-3. Department of Agricultural Economics, Kansas State University, Manhattan, KS.

DeLano, D.R., J.R. Williams, and D.M. O'Brien. 1997. An economic analysis of modifications for flood and center-pivot irrigation systems. Staff Paper 97-6. Department of Agricultural Economics, Kansas State University, Manhattan, KS.

Dhuyvetter, K.C., F.R. Lamm, and D.H. Rogers. 1994. Subsurface drip irrigation for field corn: An economic analysis. Publication L-909, Irrigation Management Series. Kansas State University Agricultural Experiment Station and Cooperative Extension Service, Manhattan, KS.

Dumler, T.J., C.R. Thompson, D.M. O'Brien, and R. Stockton. 2002a. Center-pivot-irrigated corn cost-return budget. Publication MF-585. Kansas State University Agricultural Experiment Station and Cooperative Extension Service, Manhattan, KS.

Dumler, T.J., C.R. Thompson, D.M. O'Brien, and R. Stockton. 2002b. Center-pivot-irrigated grain sorghum cost-return budget. Publication MF-582. Kansas State University Agricultural Experiment Station and Cooperative Extension Service, Manhattan, KS.

Earls, R.C., and D.J. Bernardo. 1992. An economic analysis of irrigation alternatives in the central High Plains. *Journal of the American Society of Farm Managers and Rural Appraisers* 56:18-26.

Ellis, J.R., R.D. Lacewell, and D.R. Reneau. 1985. Estimated economic impact from adoption of water-related agricultural technology. *Western Journal of Agricultural Economics* 10:307-21.

Harris, T.R., and H.P. Mapp. 1986. A stochastic dominance comparison of water conserving irrigation strategies. *American Journal of Agricultural Economics* 68:298-305.

High Plains Associates. 1982. *Six-State High Plains Ogallala Aquifer Regional Resources Study: A Report to the US Department of Commerce and the High Plains Study Council.* Austin, TX: High Plains Associates.

High Plains Study Council. 1982. *Summary of Results of the Ogallala Aquifer Regional Study, with Recommendations to the Secretary of Commerce and Congress.* Washing, DC: Economic Development Administration.

Kansas Water Office. 1982a. *Ogallala Aquifer Study in Kansas: Summary.* Topeka, KS: Kansas Water Office.

Kansas Water Office. 1982b. *Ogallala Aquifer Study in Kansas: L-P Model.* Topeka, KS: Kansas Water Office.

Kansas Water Office. 1994. *Kansas Irrigation Water Use.* Topeka, KS: Kansas Water Office.

Llewelyn, R.V., J.R. Williams, and P.L. Diebel. 1996. The economic impacts of water supply reductions: Economically optimal cropping practices on the Upper Arkansas River under varying policy conditions. Report 313. Kansas Water Resources Research Institute, Topeka, KS.

Lubben, B.D. 2001. *The 2002 Farm Bill: US Producer Preferences for Agricultural, Food, and Public Policy.* Publication 2001-02. Oakbrook, IL: The Farm Foundation.

McDonald, M.G., and A.W. Harbaugh. 1988. A modular three-dimensional finite-difference ground-water flow model. In *Techniques of Water-Resource Investigations of the United States Geological Survey,* ch. A1. Washington, DC: US Government Printing Office.

Nieswiadomy, M. 1985. The demand for irrigation water in the High Plains of Texas, 1957-80. *American Journal of Agricultural Economics* 67:619-26.

O'Brien, D.M., F.R. Lamm, L.R. Stone, and D.H. Rogers. 2000. The economics of converting from surface to sprinkler irrigation for various pumping capacities. Publication MF-2471. Irrigation Management Series, Kansas State University Research and Extension Service, Manhattan, KS.

O'Brien, D.M., D.H. Rogers, F.R. Lamm, and G.A. Clark. 1998. An economic comparison of subsurface drip and center pivot sprinkler irrigation systems. *Applied Engineering in Agriculture* 14:391-98.

O'Brien, D.M., R. Stockton, T.J. Dumler, and C.R. Thompson. 2002. Center-pivot-irrigated soybean cost-return budget. Publication MF-586. Kansas State University Research and Extension Service, Manhattan, KS.

Ogallala Aquifer Management Advisory Committee. 2001. Discussion and Recommendations for long-term management of the Ogallala Aquifer in Kansas. Topeka, KS. Kansas Water Office.

Paris, Q. 2001. Symmetric positive equilibrium problem: A framework for rationalizing economic behavior with limited information. *American Journal of Agricultural Economics* 83:1049-61.

Peterson, J.M., and D.J. Bernardo. 2003. A review of economic analyses of water policies and irrigation issues in the High Plains: 1980-2000. Research Report 36. Department of Agricultural Economics, Kansas State University, Manhattan, KS.

Schloss, J.A., R.W. Buddemeier, and B.B. Wilson, eds. 2000. *An Atlas of the High Plains Aquifer.* Kansas Geological Survey, Educational Series 14.

USDA-ERS (US Department of Agriculture, Economic Research Service). 2003. Farm and commodity policy briefing room: Glossary of policy terms. Retrieved 2 January 2003, http://www.ers.usda.gov/briefing/FarmPolicy/glossary.htm.

USDA-NASS (US Department of Agriculture, National Agricultural Statistics Service). 1998. *1997 Census of Agriculture.* Washington, DC: USDA-NASS.

USDA-NASS (US Department of Agriculture, National Agricultural Statistics Service). 2002. Online database of crop statistics. Washington, DC. Retrieved 25 July 2002, http://www/nass.usda.gov:81/ipedb/.

USDOE-EIA (United States Department of Energy, Energy Information Administration). 2001. *Annual Energy Review.* Washington, DC. Retrieved 2 January 2003, http://www.eia.doe.gov/emeu/aer/contents.html.

Westcott, P.C., and M. Price. 2001. *Analysis of the US Commodity Loan Program with Marketing Loan Provisions.* Agricultural Economic Report No. 801. Washington, DC: US Department of Agriculture, Economic Research Service.

Woods, J.J., J.A. Schloss, J. Mosteller, R.W. Buddemeier, B.A. Maxwell, J.D. Bartley, and D. Whittemore. 2000. *Water Level Decline in the Ogallala Aquifer.* Open-file Report 2000-29b (v2.0). Kansas Geological Survey. Retrieved 2 January 2003, http://www.kgs.ukans.edu/HighPlains/2000-29BDecdir.htm.


LANDSCAPE JOURNAL