

A281.9
A98A



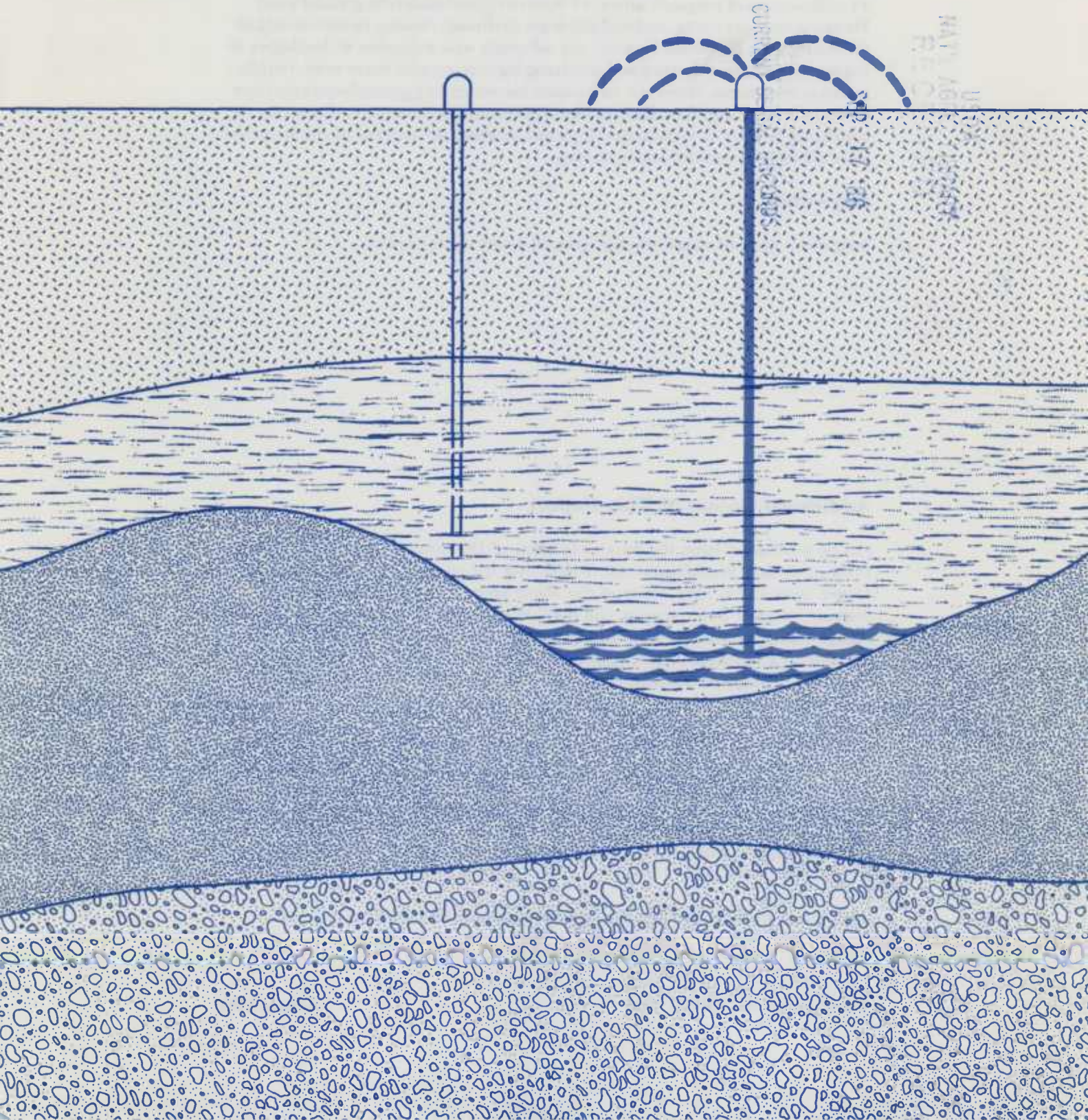
United States
Department of
Agriculture

Economic
Research
Service

Agricultural
Economic
Report
Number 555

Ground-Water Mining in the United States

Gordon Sloggett and Clifford Dickason



Abstract

Ground-water levels are declining from 6 inches to over 5 feet annually beneath 14 million acres of irrigated land in 11 States irrigated mainly by ground water. Pumping costs are rising, and well yields are declining, causing farmers to adjust their irrigation practices. Farmers are adopting new irrigation technologies to improve irrigation efficiency and are changing to crops with lower water requirements in some areas. However, techniques for conserving ground water may not extend the life of aquifers. State and local governments have passed laws severely restricting further irrigation development in about 45 percent of the irrigated area affected by ground-water mining.

Keywords

Irrigation, ground-water mining, ground-water management

Additional Copies of This Report . . .

can be purchased from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402. Ask for *Ground-Water Mining in the United States* (AER-555). Write to the above address for price and ordering instructions. For faster service, call the GPO order desk at (202) 783-3238 and charge your purchase to your VISA, Choice, MasterCard, or GPO Deposit Account. A 25-percent bulk discount is available on orders of 100 or more copies shipped to a single address. Please add 25 percent extra for postage for shipments to foreign addresses.

Microfiche copies (\$5.95 each) can be purchased from the Identification Section, National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161. Ask for *Ground-Water Mining in the United States* (AER-555). Enclose check or money order, payable to NTIS. For faster service, call NTIS at (703) 487-4650 and charge your purchase to your VISA, MasterCard, American Express, or NTIS Deposit Account. NTIS will ship rush orders within 24 hours for an extra \$10; call 800-336-4700.

The Economic Research Service has no copies for free mailing.

Contents

	Page
Summary	iv
Introduction	1
Study Area and Data Sources	1
Area	2
Crops	2
Pumping Lift and Rate of Decline	2
Rate of Change in Water Level	2
Area and Crops Irrigated	3
Area Irrigated	3
Crops Irrigated	4
Irrigators' Responses	5
Case Studies	6
Texas	6
Arizona and California	8
Kansas	9
Institutions	10
Conclusions	11
References	12
Appendix Tables	15

Summary

Ground-water levels are declining from 6 inches to over 5 feet annually beneath more than 14 million acres of irrigated land in 11 States irrigated mainly by ground water. Irrigators face three adverse effects as ground-water levels decline: (1) their pumping costs increase, (2) well yields decline, and (3) pumping efficiency decreases. The combination of these factors eventually will economically exhaust the ground-water resource. Producers of rice, grain sorghum, and grapes will be most affected in areas of ground-water decline.

In the Texas High Plains, an early ground-water irrigated area, the area irrigated with ground water has decreased by about 2 million acres since the midseventies, due partly to declines in the water level. Other areas with more ground-water resources and a shorter history of irrigation have not yet experienced a decrease in area irrigated. Studies in some of those areas indicate that significant declines in ground-water levels will not occur in this century.

Research on individual farmers' responses to declining water levels in Kansas, Arizona, and California concludes that improved irrigation equipment and procedures could overcome some of the adverse effects of the decline in ground-water levels. In these States, small changes in commodity prices affected individual farmers' decisions about irrigation more than did declining ground-water levels. Adoption of improved irrigation techniques did not decrease the amount of water used, but it did allow farmers to irrigate a larger area, according to a study of the Texas High Plains.

Most State and local governments have already passed laws directed at problems associated with declining ground-water levels. Only Arkansas and California have no specific ground-water legislation. Nine States exert some control, and the legislation in six of those States has stopped or severely reduced new ground-water irrigation in problem areas.

Ground-Water Mining in the United States

Gordon Sloggett and
Clifford Dickason*

Introduction

Water for irrigation in the United States comes from two sources: surface water and ground water. Surface water fills lakes, rivers, streams, and reservoirs, and is annually replenished by melting snow, rainfall, and seepage from ground water. Ground water occurs in aquifers and is also replenished by melting snow and rainfall, but much more slowly than is surface water. Ground water, accumulated over millions of years, was not withdrawn in significant quantities until the development of high-volume turbine pumps about 50 years ago. Ground water is being removed more rapidly than it is being replenished in several areas of the United States.

Land irrigated from ground water was estimated at 32.3 million acres in 1977 and reached 36.4 million acres by 1983 (6).¹ However, ground-water levels were estimated to be in chronic decline under about 15 million of those acres in 1977 (8). Since 1977, irrigation has significantly increased, and more information has become available on ground-water mining in some of the major areas of ground-water decline. This report makes new estimates of the area, extent, and possible consequences of chronic ground-water decline.

This report defines regions of ground-water mining, including areas and crops irrigated, rates of ground-water decline, and pumping lifts. It reports results of a more detailed analysis of the probable impact of declining water levels for selected mining areas with respect to higher pumping costs, reduced well yields, adoption of irrigation technology, and institutional restraints on ground-water use. These findings are then related to their possible impacts on irrigated agriculture and U.S. agricultural production.

*Sloggett and Dickason are agricultural economists with the Natural Resource Economics Division, Economic Research Service, U.S. Department of Agriculture, in Stillwater, OK, and Washington, DC, respectively.

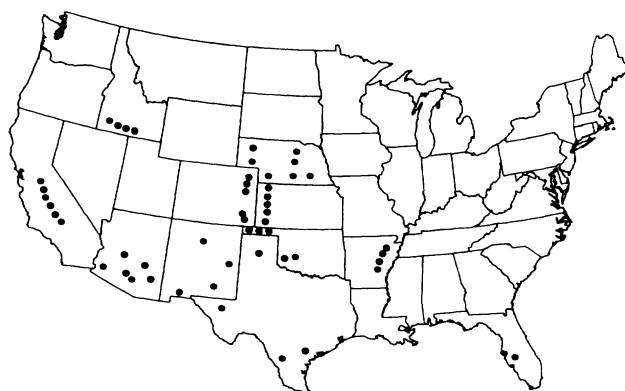
¹Italicized numbers in parentheses refer to items in the references at the end of this report.

Study Area and Data Sources

The U.S. Geological Survey (USGS) has identified major areas of chronic ground-water decline in 11 States (see figure). Each of these States irrigates more than 500,000 acres from ground water; together they account for 85 percent of the total area irrigated with ground water (6). Oregon and Washington have several small (a few thousand acres) isolated pockets of ground-water decline, but they are not included in this report.

Data sources for this report include the U.S. Department of Agriculture (USDA), USGS, the 1982 *Census of Agriculture* (9), agricultural experiment stations, State and local water agencies, and personal communications with State irrigation specialists and hydrologists. We estimated four items for the areas of ground-water decline in each of the 11 States: area irrigated, crops irrigated, pumping lift, and annual rate of decline. Except for crop data from the census, a consistent national data series is not available for estimating the other data items. Some, but not all, of the States periodically collect information for the necessary data items,

U.S. Areas of Major Ground-Water Decline



but they do not do so uniformly with respect to years or items. Thus, a time series analysis of the ground-water mining problem comparing data from the 1977 report with these latest data is not possible.

Area

Because of difficulties in defining areas with a smaller rate of decline, we included only areas where the average annual rate of decline exceeds 6 inches per year. The process of estimating the land irrigated in ground-water mining areas differed considerably among the States. For example, nearly all the ground-water irrigated areas in the Texas and Oklahoma panhandles, eastern Colorado, and western Kansas have declining water levels. The area affected by ground-water mining in these places approximates the area irrigated with ground water. However, in some parts of Nebraska and California, surface water and ground water are intermingled, resulting in fluctuating and sometimes rising ground-water levels. In other parts of those two States, ground-water levels appear stable. Thus, in California and Nebraska, estimates of the area irrigated with ground water are not a good proxy for the area of ground-water mining. An irrigation specialist was able to estimate the area of decline in California for this report (*12c*).² We were able to estimate the areas of mining in Nebraska with the aid of several maps outlining areas of water level decline and the location of irrigation wells.

The above examples indicate the variety of methods used to estimate the area of ground-water mining in the 11 States. They also illustrate the difficulties one would experience in attempting a time series analysis of changes with these data in the ground-water mining area that incorporates all 11 States.

Crops

Irrigated crop data were not generally available for just the mining areas. However, the *1982 Census of Agriculture* provides estimates of irrigated crop acreage by county (*9*). We assumed that irrigated crops are distributed evenly within a county, regardless of the decline in water level. This assumption is accurate where ground-water levels are falling in an entire ground-water irrigated area, such as in western Kansas and the Texas and Oklahoma panhandles. However, in areas with only some decline in ground-water level or where surface water is also used for irrigation, the assumed crop distribution data may be subject to error.

²Several references (10-20) are listed under each of the 11 States discussed in this report. These references are cited directly where used in the text, for example, *12c*. Some of the references listed under the States are not cited directly, but rather are cited as a group as a source for data used in the appendix.

Pumping Lift and Rate of Decline

Pumping lift is the static water level distance plus drawdown. Static water level in a well is the distance from ground level to water level when no water is being pumped. Drawdown is the difference between static water level and the water level in the well when it is being pumped. Measurements of static water level are taken annually by USGS and by State and local water agencies. Pumping lift varies among and within the ground-water mining areas because of differences in static water levels and in drawdown. Drawdown may vary because of differences in the water-bearing material (aquifer), well design, pumping rate, and other technical factors. Drawdown data are not generally available, but hydrologists indicated that an increase of 10 percent in the static water level is a reasonable estimate for drawdown.

We used annual changes in static water levels to estimate rates of decline. We used many data sources for these estimates, but employed data for the most recent 5-year period (when available) to estimate the annual rate of decline. Variations in decline rates between years and within mining areas are commonplace. Rates of decline vary with annual rainfall. In wet years, irrigation requirements are usually less and more water is available to recharge the aquifer (but not enough to overcome the long-term decline). The opposite is true, of course, for dry years. Rates of decline also vary within an area for several other reasons, including density of irrigation wells, structure of the aquifer, the ability of surface water to penetrate the aquifer (which affects the recharge rate), and different water requirements among the crops irrigated.

We calculated an average pumping lift and annual rate of decline for each study area (app. tables 1-22). Table 1 summarizes these estimates by State. Pumping lifts and annual rates of decline differ significantly within an area. However, because finding and presenting such detail for this report are extremely difficult, using an average for each area is an appropriate means of comparing ground-water mining areas.

Rate of Change in Water Level

Good records of annual measurements of water level over an extended period are not available for most areas of ground-water mining. However, two ground-water management districts in the Texas High Plains have had a water-level measurement program since the fifties (*20c, 20e*). These data provide some insight into the rate of decline over time. Studies of 10-year moving averages indicate that the average annual rate of decline has been reduced by about 0.5 foot since the fifties in the southern Texas High Plains. By the same criterion,

the annual rate of decline has been reduced by about 0.75 foot in the northern Texas High Plains. The current 10-year average annual rate of decline is about 2 feet in the northern High Plains and 1.25 feet in the southern High Plains.

Several reasons for the lower rate of decline in recent years are possible: (1) well yields have declined along with declining water levels, reducing the amount of water that may be pumped in a given period; (2) farmers have become more efficient irrigators by adopting more efficient irrigation techniques with existing technology or by shifting to more efficient technology, thus reducing water application rates; (3) crops with lower water requirements are being substi-

tuted for crops with higher water requirements; and (4) the amount of irrigated land is declining because of economic exhaustion of the aquifer in some areas. Much higher energy prices have had a major impact on items (2) and (4). All the above have occurred in the Texas High Plains, but it was not possible in this report to analyze which item has most reduced the rate of decline.

Although sufficient data on long-term annual water levels are not available in most other ground-water mining areas, the rate of decline will probably diminish in some of those areas because many of the conditions existing in the Texas High Plains are characteristic of other mining areas.

Table 1—Lift and rate of decline for areas of ground-water decline in major ground-water irrigated States¹

State	Average pumping lift	Average annual rate of decline
	<i>Feet²</i>	
Arizona	75-535	2.0-3.0
Arkansas	50-120	.5-1.3
California	100-260	.5-3.5
Colorado	175-275	2.0
Florida	250	2.5
Idaho	200-375	1.1-5.0
Kansas	190-275	1.0-4.0
Nebraska	25-250	.5-2.0
New Mexico	100-200	1.0-2.5
Oklahoma	100-275	1.0-2.5
Texas	50-300	1.0-4.0

¹See appendix tables 1-22.

²The amount of lift and the annual rate of decline are the ranges of averages in the States. These figures do not indicate that the State average is between the two rates.

Area and Crops Irrigated

A discussion of the area and the crops irrigated in areas of ground-water decline will help put the problem of ground-water mining in perspective.

Area Irrigated

Table 2 summarizes ground-water mining areas irrigated in the 11 major ground-water irrigated States. The 31 million acres irrigated with ground water in those States represented 85 percent of all land irrigated with ground water in the United States in 1983 (6). Ground-water levels were declining beneath 14 million of those acres. The appendix tables show ground-water mining areas, acres irrigated, crops irrigated, average feet of lift, and average annual decline in each area of each State in the study.

Table 2—Area irrigated with declining ground-water supplies in 11 major ground-water irrigated States¹

State	Total ground-water irrigation		Decline area irrigated ²		Percentage of 1983 area irrigated (col 4/2)
	1977	1983	1977	1983	
	-----1,000 acres-----				<i>Percent</i>
Arizona	940	938	³	606	65
Arkansas	1,400	2,337	³	425	18
California	4,388	4,265	³	2,068	48
Colorado	1,650	1,660	570	590	36
Florida	1,076	1,610	³	250	16
Idaho	1,149	1,450	³	223	15
Kansas	3,083	3,504	1,950	2,180	62
Nebraska	5,855	7,025	1,842	2,039 ⁴	29
New Mexico	760	805	560	560	70
Oklahoma	730	645	507	523	81
Texas	7,846	6,685	6,425	4,565 ⁴	73
Total	28,877	30,924	³	14,029	45

¹Total ground-water area irrigated was estimated for 1977 and 1983 (6). Decline area irrigated was estimated from data for the latest year available (see app. tables).

²Only areas experiencing at least a 6-inch average annual decline are included in these estimates.

³Data insufficient to make time series comparisons.

⁴Data are for 1984.

Table 2 presents data from an earlier study of ground-water mining for comparison purposes (8). Data deficiencies do not allow for a time series analysis of data from the mining areas. However, some data for the Great Plains States were of high enough quality to indicate the degree of change in the area of ground-water decline. The area irrigated with ground water in the 11-State study area increased from 28.9 million acres to 30.9 million acres between 1977 and 1983, and the area of decline increased in all States, except Texas, with sufficient data to estimate that change. The area of ground-water decline in Texas was nearly 2 million acres less in 1984 than in 1977. The economic exhaustion of parts of the aquifer was the main reason for the decline in irrigated acres. A combination of factors, including increased pumping lifts, reduced well yields, increasing energy prices, and low commodity prices, led to the economic exhaustion. Although other States face similar conditions, Texas relies more than any other State on natural gas for pumping, and the price of natural gas has risen much faster than that for other types of energy. Texas also began extensive use of ground water for irrigation earlier than other Plains States and started out with less ground water in storage.

Conditions which economically exhaust the aquifers apparently do not exist in other Great Plains States because they have increased ground-water irrigation and area of decline since the late seventies. However, the aquifer in the Great Plains is essentially finite, so that trend cannot continue indefinitely. A recent study of irrigation in the area indicates a probable decline in ground-water irrigation in all of the Great Plains States, except Nebraska, by 2020 (2). The aquifer in Nebraska is extensive, with large well yields, modest pumping lifts, and slowly declining water levels, compared with those in other Plains States. California is currently transferring surface water into some of its areas of ground-water decline, and the Central Arizona Project, when complete, will transfer surface water to areas of ground-water decline in Arizona. Texas and Oklahoma have studied surface water transfer projects, but have no plans to implement them. The impact of declining water levels will be lessened by the use of surface water transfers, whereas areas of decline without such transfers must look for other alternatives to deal with the problems created by reduced ground-water irrigation.

The water level in over 50 percent of the area irrigated with ground water in Arizona, Kansas, New Mexico, Oklahoma, and Texas is declining; almost 50 percent in California is declining (table 2). Even more significant, the water level of 45 percent of all ground-water irrigated land is declining. Although this problem is serious, one should put it into national perspective with respect to agricultural production by comparing the acres and crops grown in the ground-water mining areas with total U.S. crop production.

Crops Irrigated

To appreciate more fully the contribution of agricultural production from ground-water mining areas, one should ask: What if production on all irrigated land in the ground-water mining areas were to cease? Total sales from irrigated farms in 1982 represented 30 percent of all farm sales reported by the *1982 Census of Agriculture* (9). The census reported about 50 million acres of irrigated land in 1982. The 14 million acres affected by ground-water decline would have been 28 percent of total irrigated land. If one assumed, rather unrealistically, homogeneous sales from all irrigated acres, total farm sales would decline by 8.4 percent (0.28×0.30), if the entire mining area were to cease production. However, there are two major problems with this "what if" question and answer. First, production will not cease when the water runs out, except in the desert. Dryland production will continue in many mining areas. Second, the value of production from an irrigated acre of grapes in California differs dramatically from the value of production from an irrigated acre of grain sorghum in the High Plains of Texas. Thus, to better comprehend the potential impact of ground-water decline on agricultural production, one must consider the crops affected.

The impact of ground-water decline on some crops (cotton, 22 percent; citrus, 15 percent; grapes, 33 percent; grain sorghum, 16 percent; and rice, 13 percent) would be more significant than on others (table 3). However, the size of the impact on any one crop would depend on available alternatives when farmers decide to discontinue irrigation. Alternatives are to grow the same crop under dryland conditions, to shift to a crop that can be grown with available natural moisture, or to go out of crop production. These decisions and their timing in the various areas of decline depend on economic conditions regarding

Table 3—Crops harvested in the United States and in areas of ground-water decline¹

Crop	Total U.S. acres harvested ²	Acres harvested in decline areas	Decline area as percentage of total acres harvested
	<i>Million acres</i>		<i>Percent</i>
Alfalfa	23.9	0.9	4
Cotton	8.9	2.0	22
Corn	77.9	3.2	4
Citrus	1.3	.2	15
Grapes	.9	.3	33
Grain sorghum	13.4	2.1	16
Peanuts	1.2	.1	8
Rice	3.2	.4	13
Small grain	89.7	2.8	3

¹See footnote 1, table 2.

²Source: (7).

the profitability of irrigation and the aquifer characteristics peculiar to the respective areas.

By assuming continued favorable economic conditions for irrigation in mining areas, one can estimate crop alternatives as well yields gradually decline and as irrigation begins to decline. Dryland corn is a feasible alternative to irrigated corn in much of Nebraska (table 4). Grain sorghum is a feasible alternative to irrigated cotton in much of Texas. Irrigated wheat would probably go to dryland wheat, except in Arizona and California. Nearly all the corn and alfalfa grown in ground-water irrigated States, except Nebraska, could not be grown without irrigation because rainfall is not sufficient for dryland production. Much of the acreage devoted to irrigated corn and alfalfa in Colorado, Kansas, New Mexico, Oklahoma, and Texas would probably be used for the dryland production of grain sorghum or wheat.

Almost no crops can be produced without irrigation in the desert areas of Arizona, California, and New Mexico. Rice in Arkansas and Texas, citrus in Florida, and grapes in California could not be grown profitably in their present locations without irrigation.

Again, if one assumes favorable economic conditions for irrigation, crop production will adjust gradually to declining ground-water levels. Adequate time exists to relocate the production of affected crops to areas that will support their production. For example, areas in California with adequate water supplies and climate could pick up any lost grape and citrus production. Rice production in Arkansas and Texas might transfer to other parts of those States or to other rice-producing States. Grain crop production could be transferred to other grain-producing areas. Predicting shifts in crop

production caused by declining ground-water levels requires a knowledge of when, where, and which crops will shift and of the cost/price relationships at that time.

Irrigators' Responses

This study focuses on what could happen to crop production should ground-water irrigation become unprofitable because of economic exhaustion of the aquifer. However, irrigators would probably make some adjustments prior to economic exhaustion as well yields and declining water levels slowly eroded their profits.

Declining water levels increase pumping lifts and reduce well yields which, in turn, boost pumping costs. People often suggest improving irrigation efficiency to reduce the amount of water pumped to overcome these problems. A recent survey of 956 randomly selected persons from 14 counties in six High Plains States shows that improved irrigation efficiency is the first choice (93 percent chose this alternative) among many alternative adjustments in response to potential ground-water depletion (4). That choice seems logical because it allows irrigators to use less water to maintain or perhaps to improve yields without reducing their irrigated acreage.

Application efficiency of irrigation systems can range from 40 to over 90 percent (table 5). Efficiency relates to the amount of water that must be applied to the field to satisfy the water requirements of crops. If the "ultimate" system were available, an irrigator would have to pump and apply only one acre-inch of water to supply the crop requirement. However, evaporation, tailwater runoff, seepage, and percolation of irrigation water below a crop's root zone all inhibit the "ultimate"

Table 4—Crops irrigated in areas of ground-water decline in major ground-water irrigated States¹

State	Alfalfa	Cotton	Corn	Citrus	Grapes	Grain sorghum	Peanuts	Rice	Small grain	Other	Total
	<i>1,000 acres</i>										
Arizona	104	211	—	—	—	57	—	—	180	54	606
Arkansas	—	3	—	—	—	—	—	261	—	161	425
California	242	613	87	—	258	—	—	—	295	573	2,068
Colorado	44	—	315	—	—	56	—	—	73	102	590
Florida	—	—	—	200	—	—	—	—	—	50	250
Idaho	52	—	—	—	—	—	—	—	106	65	223
Kansas	122	—	664	—	—	542	—	—	683	169	2,180
Nebraska	64	—	1,456	—	—	123	—	—	44	352	2,039
New Mexico	136	72	55	—	—	96	—	—	126	75	560
Oklahoma	37	17	31	—	—	181	26	—	213	18	523
Texas	115	1,108	568	—	—	1,019	25	133	1,029	568	4,565
Total	916	2,024	3,176	200	258	2,074	51	394	2,751	2,187	14,029

— indicates no crop grown in decline area.

¹See footnote 1, table 2.

Source: Appendix tables 1-22.

system. For a sprinkler or gravity system that is 75 percent efficient, irrigators would have to pump and distribute 1.33 acre-inches of water to satisfy a 1-acre-inch crop requirement. If an irrigator uses a 40-percent-efficient gravity system, 2.5 acre-inches of water would have to be pumped and distributed to meet a crop requirement of 1 acre-inch.

All irrigators would presumably choose the most efficient system. But what is most efficient for one irrigator may not be so for another. The physical properties of the land irrigated and principles of economics may cause irrigators to make different choices. Gravity irrigation systems require land with enough water-holding properties to allow water applied at one end of the field to flow to the other end without too much water percolating below a crop's root zone. Thus, irrigators with very porous, sandy soils cannot use gravity systems and must use high-cost sprinklers. Regardless of soil type, gravity systems require smooth, gently sloping land for irrigation water to flow evenly at the proper speed over the field. If the land to be irrigated cannot be properly formed, either economically or physically, a sprinkler system must be used.

Principles of economics may also dictate the choice of irrigation system. Sprinkler or improved gravity systems generally require significantly more investment than does an unimproved gravity system. Irrigators who can pump and distribute irrigation water cheaply with an unimproved gravity system may use this technically inefficient system at lower total cost than a more efficient system. For example, an irrigator with a system that is 40 percent efficient and that costs \$10 per acre foot would have an irrigation water requirement cost of $(1/0.4 \times \$10)$ \$25. If that same irrigator were to install a system to increase efficiency to 80 percent, costs could increase from \$10 to \$25 per acre-foot; irrigation

costs would be $(1/0.8 \times \$25)$ \$31.25. Thus, in this not unrealistic example, the more technically inefficient system is the least cost system. But as water levels and well yields decline, irrigation costs increase, thus making more technically efficient, but higher cost, systems more attractive to the irrigator.

One purpose of this study was to determine how irrigators might adjust to declining water levels. Aside from discontinuing irrigation, they might adopt more efficient irrigation systems. Although irrigators need not be in a situation with a declining water level to consider adopting more efficient irrigation systems, they have more incentive to do so when their costs increase faster than those not experiencing a decline.

Case Studies

Several researchers have recently completed case studies on the feasibility of adopting more efficient irrigation systems in selected ground-water mining areas (1, 3, 5). Ellis studied the Texas High Plains; Pfeiffer examined an area in the Northern Great Plains; and Hoyt looked at ground-water mining areas in Arizona and California. These three researchers did not use the same methodology, consider the same irrigation technology, or look at the problem from the same perspective; but all shed some light on adjustments that irrigators are likely to make as their water levels decline.

Texas

Ellis used a recursive linear programming model for his analysis. In addition to the usual linear programming crop and acreage restraints, he included restraints for the relevant ground-water resource situations and soil types in the Texas High Plains. Ellis selected a 40-year study period beginning in 1980. The objective of his model was to maximize net profits from the specified crop mix, given the irrigation technology selected for analysis: limited tillage, improved furrow, and low-energy precision application (LEPA). Limited tillage qualified as an irrigation technology because irrigation water requirements are lower than those for conventional tillage. The improved furrow category included alternate furrow irrigation, furrow diking, surge flow, automated flow, and tailwater recirculation pits with an assumed efficiency of 80 percent. LEPA technology is an adaptation of center pivot or side roll sprinkler systems that have drop tubes emitting water at very low pressure close to the ground. LEPA has an application efficiency of 92 percent.

Ellis analyzed the impact of technology adoption over time on the Texas High Plains by combining the three technologies discussed into four different scenarios: (A)

Table 5—Irrigation efficiency for selected irrigation systems

System	Efficiency	Water needed to supply 1 acre-inch to the crop
	Percent	Acre-inches
Ultimate	100	1.00
Drip	92	1.09
Low-energy precision application	92	1.09
Sprinklers ¹	75-85	1.18-1.33
Improved gravity ²	75-85	1.18-1.33
Gravity	40-60	1.67-2.50

¹Includes side roll, solid set, traveling gun, high- and low-pressure center pivot, and other mechanical move systems.

²Includes tailwater recovery and surge flow systems as well as precision land leveling.

use of existing irrigation systems and conventional tillage practices, (B) adoption of limited tillage, (C) conversion of conventional tillage to improved furrow combined with limited tillage, and (D) conversion to conventional sprinklers on furrow-irrigated acreage and a limited amount of conversion to LEPA systems along with changes (B) and (C).

Ellis selected the rate of adoption for each technology based on the best estimates of experts familiar with the area (1). Thus, the model did not permit selection of the appropriate technology to deal with higher pumping costs and reduced well yields caused by declining water levels. Ellis estimated the impact of the assumed rate of technology adoption on irrigation in the Texas High Plains instead. His analysis of the four scenarios focused on several aspects of irrigation including water use, change in dryland and irrigated acreage, distribution systems used, and net returns. Table 6 shows the results of that analysis. The first scenario in the model assumes no new technology adoption during the 40-year study period, whereas the next three scenarios allow for successive adoption of more efficient irrigation systems. Ellis evaluated each scenario at 10-year intervals.

Water Use. The more efficient the irrigation system, the less water must be pumped to satisfy a crop's

irrigation water requirement. Thus, one would expect water use to be less in each evaluation period as the level of technology increased, as in B through D. However, as limited tillage, improved furrow, and LEPA systems came into the model solutions, water use remained essentially constant when compared, in the same period, with water use when no new technology was allowed in the model. In 2010, for example, 4.6 million acre-feet of irrigation water were used with existing technology; the largest change in water use was only 3.7 percent with the highest level (D) of technology adoption. This finding indicates that irrigators would take the water saved by technology adoption and apply it to more acres—to 27.7 percent more acres in 2010. Although water use per acre would decline, the model solutions indicate the same amount of water would be used. Thus, although new technology may not extend the life of the aquifer, it may allow more acres to be irrigated during that lifespan.

Change in Dryland and Irrigated Acreages. The model estimated dryland cropland would increase radically and irrigated land would decrease during the 40-year study period as the aquifer was slowly depleted. Technology adoption slowed the change to dryland production and allowed more land to be irrigated in each evaluation period. The last evaluation period, 2020, and the highest level of technology adoption, D,

Table 6—Temporal regional analysis summary, Texas High Plains

Year	Scenario A			Percentage change from A		
	Category	Unit	Value	B	C	D
			<i>Dollars</i>	----- <i>Percent</i> -----		
1981	Water use	1,000 a/f*	7,515	0.1	0.1	0.2
	Dryland	1,000 acres	3,820	-.3	-.7	-.6
	Irrigated	do.	6,091	.2	.5	.4
	Net return	\$1 million	1,116	8.1	8.4	9.1
1990	Water use	1,000 a/f	7,504	.1	0	.1
	Dryland	1,000 acres	4,198	-6.8	-9.8	-19.2
	Irrigated	do.	5,713	5.0	7.2	14.1
	Net return	\$1 million	1,037	14.4	20.6	28.5
2000	Water use	1,000 a/f	6,905	-.6	-.8	-.2
	Dryland	1,000 acres	4,859	-1.1	-10.0	-17.9
	Irrigated	do.	5,052	1.0	9.6	17.2
	Net return	\$1 million	911	20.4	26.9	36.0
2010	Water use	1,000 a/f	4,606	-.3	3.3	3.7
	Dryland	1,000 acres	6,966	0.	-8.8	-11.7
	Irrigated	do.	2,945	9.2	20.9	27.7
	Net return	\$1 million	661	30.7	38.3	43.7
2020	Water use	1,000 a/f	2,275	2.2	1.1	1.3
	Dryland	1,000 acres	8,607	-2.4	-4.6	-6.3
	Irrigated	do.	1,304	15.8	30.4	41.7
	Net return	\$1 million	520	38.5	43.5	48.1

*a/f indicates acre-feet.
Source: (1).

showed 6.3 percent fewer dryland acres and 41.7 percent more irrigated acres than would have been expected if no new technology had been adopted.

Net Return. Net returns declined from \$1.1 billion to to \$0.5 billion between 1981 and 2020 as dryland farming replaced irrigated farming in the Texas High Plains under scenario A assumptions. However, returns were significantly higher at all levels of technology adoption in all periods. They would have been nearly 50 percent greater at the end of the period with the highest level of technology adoption.

Arizona and California

Hoyt used a partial budgeting procedure to study technology adoption for the ground-water mining areas of Arizona and California. His study was limited to budgets available from secondary sources. Thus, budgets for some of the very new or experimental irrigation technology, such as surge flow and LEPA, were not available for Arizona and California and were not included in his analysis. Technologies considered for Arizona were: (1) furrow with siphon tubes directing

water down the furrows, (2) furrow with a tailwater recovery system, (3) furrow with a modified slope, and (4) furrow with a level basin. Efficiencies assumed for the irrigation systems were 55, 65, 80, and 85 percent, respectively. Technologies considered for California were: (1) technologies considered for Arizona, (2) furrow with gated pipe, (3) furrow with siphon tubes and a modified slope, (4) furrow with gated pipe and a modified slope, and (5) hand-move sprinkler system for fields not suited to gravity flow systems. Efficiencies assumed for these systems were 55, 65, 80, 85, and 75 percent, respectively.

Hoyt modified budgets for the typical crops grown in Arizona and California to reflect the cost of growing those crops with each of the respective irrigation technologies. He determined break-even costs of water for each alternative (tables 7, 8). He considered three levels of crop prices based on prices received from 1974 to 1983. The medium price was the 10-year average, and the low and high prices were the extremes during the 1974-83 period. With this break-even cost information and with estimated costs of production from the budgets for each irrigation system, one can compare

Table 7—Break-even cost of water for various crop price levels, Pinal County, AZ^{1,2}

Crop	Furrow			Tailwater recovery			Modified slope			Level basin		
	L	M	H	L	M	H	L	M	H	L	M	H
<i>Dollars per acre-inch</i>												
Alfalfa	1.2	2.5	4.3	1.8	3.3	5.4	2.9	4.8	7.7	3.1	5.0	7.9
Cotton	2.9	5.6	9.1	4.9	8.5	13.1	7.0	11.6	17.4	7.9	12.7	18.9
Sorghum	.7	2.0	2.7	.9	2.4	3.2	1.5	3.3	4.2	1.9	4.0	5.0
Wheat	1.1	2.1	4.0	1.9	3.0	5.3	3.3	4.8	8.0	3.3	4.9	8.0

¹Based on crop prices from table 1, crop yields and costs from table 2.

²L = Low

M = Medium

H = High

Source: (2).

Table 8—Break-even cost of water for various crop price levels, Kern County, CA^{1,2}

Crop	Furrow			Gated pipe			Sprinkler			Modified slope			Gated pipe/modified slope		
	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
<i>Dollars per acre-inch</i>															
Alfalfa	1.6	3.2	5.8	2.2	4.2	7.4	2.2	4.9	8.9	3.1	5.8	9.7	4.2	7.5	12.4
Barley	.9	3.0	4.3	1.4	3.9	5.6	1.5	4.8	7.0	2.5	5.8	8.0	3.4	7.4	10.0
Cotton	3.4	6.7	10.9	4.6	8.7	13.9	5.0	10.0	16.2	5.8	10.8	17.0	7.9	14.0	21.7
Wheat	3.3	4.7	7.4	4.4	6.1	9.5	5.1	7.3	11.7	6.0	8.2	12.6	8.0	10.8	16.2

¹Based on crop prices from table 1, crop yields and costs from table 2.

²L = Low

M = Medium

H = High

Source: (2).

break-even water costs with estimated water costs and determine which systems will allow an irrigator to at least break even. For example, if an Arizona alfalfa grower had an estimated water cost of \$4.90 per acre-inch and received a medium price, that grower would have to use a level basin irrigation system to at least break even (table 7, line 1).

Hoyt estimated 1985 ground-water costs of \$4.30 and \$3.75 per acre-inch, respectively, for Pinal County, AZ, and Kern County, CA. In Arizona, only cotton has a break-even water cost exceeding 1985 water costs for all irrigation systems and price levels (table 7). Sorghum can be profitably grown only with the most efficient irrigation system, and then only if crop price levels are high. Cotton and wheat in California have break-even water costs above 1985 water costs for every situation except the low product price level for the basic furrow system. Alfalfa and barley are viable in California, except when crop prices are low.

Hoyt modified 1985 water costs to account for changes in irrigation costs that occur as the water level declines. One can use this information to make a break-even analysis of adopting irrigation technology under conditions of declining water. For example, assume that cotton has a break-even water cost of \$2.50 per acre-inch in Arizona with technology (1) with 250 feet of pumping lift and an average annual decline of 5 feet, which increases water costs by \$0.10 per acre-inch per year. If the current water cost is \$2.00 per acre-inch, it will take 5 years of ground-water decline before profits reach zero. If cotton is the most profitable crop alternative, the irrigator can shift to a more efficient technology with a higher break-even water cost, and thereby restore profits to cotton. Using the above procedure, Hoyt analyzed crop and technology alternatives to determine how irrigators might overcome the problem of ground-water decline.

Hoyt concluded that the impact of declining ground water on water cost was minimal, but one could expect both low commodity prices and reduced production of barley and alfalfa in California and of sorghum in Arizona. Producers would continue to grow cotton in Arizona and California and wheat in California with low crop prices, regardless of the irrigation system used. If high crop prices prevail, all crops except sorghum would be profitable in the foreseeable future, even with declining ground-water levels, if producers used any irrigation system above the basic furrow system. Hoyt also concluded that the modified slope or level basin in Arizona and the modified slope or gated pipe systems in California were the most profitable system conversions of those he examined. He also determined that crop price levels will affect crops, acreages, and irrigation system adoption more than will cost increases resulting from declining ground-water levels.

Kansas

Pfeiffer selected a 10-county area in northwest Kansas for his study of technology adoption by irrigators in ground-water mining areas. Like Hoyt, he used partial budgeting and break-even analysis in comparing irrigation costs for various irrigation systems to determine which systems offered irrigators in declining ground-water situations the best alternatives. Pfeiffer considered the following systems: (1) siphon tubes; (2) three gated pipe systems (namely, tailwater recovery, surge flow with design leveling, and partial leveling); and (3) high-pressure center pivot and low-pressure center pivot. The low-pressure center pivot Pfeiffer considered is not the same as the LEPA system Ellis used in his analysis of Texas. It is a modification of a high-pressure system employing low-pressure sprinkler nozzles.

Pfeiffer constructed budgets for each irrigation system for crops commonly grown in the area: corn, wheat, grain sorghum, and alfalfa. Pfeiffer modified each budget to account for an average annual decline of 2.5 feet over a 10-year period. Table 9 shows costs of production for the crops and for four of the distribution systems. However, it does not show higher cost siphon tube and tailwater recovery systems.

For his break-even analysis, Pfeiffer estimated 1984 prices received per bushel for corn (\$2.50), wheat (\$3.00), and grain sorghum (\$2.10), and per ton for alfalfa (\$50). Natural gas, the lowest cost fuel for pumping water, was also used in the analysis. With current prices, irrigators cannot break even by growing wheat with any system, grain sorghum with any center pivot, or alfalfa with a high-pressure center pivot. Production costs for other crops and systems appear below or very near the break-even point. The surge flow system has the lowest production costs of all systems Pfeiffer considered. Changes in production costs from increasing the pumping lift 25 feet over the 10-year evaluation period were very small—a few cents per bushel and about a dollar per ton for alfalfa.

Pfeiffer concluded, as did Hoyt, that normal changes in commodity prices affect irrigators profits far more than do current cost changes attributable to ground-water mining. This situation will be especially true in the near future (5-10 years). However, as well yields begin to decline, irrigators will be forced to make some decisions concerning crops and irrigation systems. Pfeiffer determined that surge flow and low-pressure center pivot were the least-cost furrow and sprinkler systems available and were the most likely to be selected, depending on soil type and topography. As for crop production, he observed changes in the crop mix of an area in west central Kansas near his study area that was experiencing sharp declines in well yields. Corn and alfalfa production in that area was reduced to near zero,

and wheat and grain sorghum continued to be partially irrigated. That is, they received irrigation water only at planting or perhaps once more during the growing season. Although time constraints did not allow him to analyze these alternatives, Pfeiffer believes that this crop pattern is the one most likely to be maintained in the long run.

Ellis, Hoyt, and Pfeiffer all concluded from their studies of ground-water mining that improved irrigation systems have the potential to cut irrigation costs and can affect the future of irrigation in ground-water mining areas. They also concluded that irrigated crop patterns would change as a result of higher costs and lower well yields. However, each case study found that the most influential economic forces in determining the future of ground-water irrigation were not those directly affected by ground-water mining, but were the prices received for commodities and the cost of energy to pump the water.

Institutions

There is another consideration regarding the future of ground-water irrigation in ground-water mining areas. Use of ground water for irrigation is institutionally restricted in some of the 11 States included in this study. These restrictions could affect ground-water mining and the future use of ground water for irrigated agriculture. Although the Federal Government does not regulate ground-water use for irrigation, several States have passed legislation that controls ground-water use for irrigation in different degrees (7). However, although both Arkansas and California have significant ground-water mining problems, neither has any current restriction on the use of ground water for irrigation.

The remaining nine States do regulate use, and six—Arizona, Colorado, Idaho, Kansas, Nebraska, and New Mexico—have legislation aimed directly at ground-water mining. Florida, Oklahoma, and Texas have no special legislation dealing with ground-water mining.

For legislation to have any impact on ground-water mining, it must affect the quantity of water that irrigators may pump. This objective may be accomplished by a restriction on the quantity of water pumped from any one well and/or a restriction on the number of wells drilled. All six States that have legislation dealing with ground-water mining have the power to limit wells and pumping within designated problem areas. The legislation of each of the six States generally establishes a procedure to determine acceptable levels of ground-water use for irrigation, and it limits pumping and the number of wells so as not to exceed those levels.

The effect of the legislation in designated problem areas in Arizona, Colorado, Idaho, and New Mexico has been to stop additional irrigation. However, some irrigation development has occurred in mining areas in Kansas and Nebraska. Arizona's 1980 ground-water legislation goes further than that of any other State. It calls for a phased-in reduction in the use of ground water for irrigation accomplished by mandatory water conservation or by the retirement of irrigated land. Oklahoma and Texas limit the number of wells by imposing spacing requirements, but they do not prevent the drilling of wells in ground-water mining areas. Florida requires a consumptive use permit which regulates the quantity of water irrigators may use.

Attempts by the six States to deal with ground-water mining have affected irrigated agricultural land dif-

Table 9—Total costs per unit of production by lift levels, natural gas at \$3.00 per 1,000 cubic feet

Crop ¹	Unit	Lift levels						
		150 ft.	160 ft.	175 ft.	150 ft.	160 ft.	175 ft.	
<i>Dollars</i>								
			----- <i>High pressure</i> -----			----- <i>Low pressure</i> -----		
Center pivot:								
Corn	Bushel	2.48	2.49	2.52	2.41	2.43	2.45	
Wheat	do.	4.08	4.10	4.13	3.99	4.01	4.04	
Grain sorghum	do.	2.38	2.39	2.40	2.33	2.34	2.36	
Alfalfa	Ton	50.96	51.40	52.06	48.91	49.38	50.04	
			----- <i>With surge flow</i> -----			----- <i>With partial treatment</i> -----		
Gated pipe:								
Corn	Bushel	2.04	2.06	2.08	2.10	2.12	2.14	
Wheat	do.	3.13	3.15	3.17	3.18	3.20	3.24	
Grain sorghum	do.	1.93	1.94	1.95	1.96	1.97	1.99	
Alfalfa	Ton	39.06	39.46	40.11	40.73	41.26	42.12	

¹1984 estimated price received: corn, \$2.50; wheat, \$3.00; grain sorghum, \$2.10; alfalfa, \$50.00.
Source: (4).

ferently.³ Those States with only a small percentage of their irrigated area affected by ground-water mining (Idaho, Nebraska, and Colorado) will be less affected than States with a high percentage of affected area (New Mexico, Arizona, and Kansas). For example, Idaho has only 16 percent of its area irrigated with ground water affected by mining, and it places strict controls on any new irrigation development. In contrast, New Mexico has 70 percent of its ground-water irrigated area under control. Statistics on ground-water irrigation collected between 1974 and 1983 indicate that total irrigation with ground water increased 21 percent in Idaho, whereas ground-water irrigation in New Mexico remained constant.

Undeveloped ground-water resources and favorable economic conditions will surely influence any State's growth in irrigation outside control areas. Growth of ground-water irrigation from 1974 to 1983 in Colorado, with 36 percent of ground-water irrigated area in a mining situation, differed markedly from that in Nebraska, with 29 percent. Colorado's ground-water resources were largely developed, and irrigation from that source grew by only 4 percent during the period; irrigation in Nebraska, with large undeveloped ground-water resources, grew by 40 percent. Thus, conditions outside controlled mining areas, as well as the extent of control, can significantly influence what happens to irrigated agriculture in a State.

Arkansas and California have no control over ground-water use for irrigation, but they contain nearly 20 percent of the total ground-water mining area (table 2). Florida, Oklahoma, and Texas contain 38 percent of the total ground-water mining area, yet they exert little control over ground-water mining. The six States that attempt to control ground-water mining contain only 6.2 million (44 percent) of the 14 million acres in ground-water mining areas. Approximately 36 million acres were irrigated with ground water in 1983 (6). Use of ground water for irrigation is closely regulated in only 17 percent of all areas irrigated with ground water nationwide. If all irrigation in the United States is considered, including the nearly 15 million acres irrigated from surface water, the impact of these regulations on irrigated agricultural production is even less significant.

Conclusions

Over 14 million acres of U.S. land irrigated with ground water have water levels that decline by over 6 inches per year. Average annual rates of decline range up to over 5 feet per year in the 11-State study area. Declining

water levels increase pumping costs and eventually deplete the ground-water resources. The 14-million-acre estimate is 1 million acres smaller than a similar estimate made for the late seventies. The reduced ground-water mining area was a result of a decline in irrigation in the Texas High Plains caused by higher pumping costs and a depleting aquifer. Although ground-water mining is a serious problem, total U.S. acres irrigated with ground water increased by over 2 million from 1977 to 1983. In the Great Plains, where ground-water mining is widespread, analysts see significant quantities of ground water available for irrigation beyond the year 2020, even in the Texas High Plains.

Ground-water mining seems not to pose a significant national threat to irrigated agriculture in the foreseeable future. Significant changes may be in store for the areas affected by ground-water mining; however, some areas will be affected sooner and more extensively than others. Areas showing rapid rates of decline in ground-water levels and high pumping lifts are likely candidates for significant changes. States containing large land areas with high pumping lifts (more than 200 feet) and rapid rates of decline in ground-water levels (more than 3 feet per year) include parts of Arizona, California, Idaho, Kansas, Texas, and the Oklahoma Panhandle.

In Texas, ground-water irrigated land declined 15 percent in the past few years due partly, at least, to ground-water mining. Texas is unique because it has a relatively long history of extensive ground-water mining, and its aquifer was less plentiful than were the aquifers of some of the other States. However, other States with significant ground-water mining will eventually have to adjust their ground-water irrigation.

The kinds of adjustments that one can expect to make because of higher pumping costs and reduced well yields (aside from the ultimate adjustment of ceasing irrigation) include changing to crops requiring less irrigation water and adopting more efficient irrigation systems.

In his study of ground-water mining in the Texas High Plains, Ellis analyzed the impacts of a given rate of adoption of more efficient irrigation systems between 1980 and 2020. He drew three conclusions: (1) ground-water use would probably change little with the adoption of efficient irrigation systems because, as irrigators reduce application rates per acre, they are likely to increase irrigated acres; (2) although irrigation would decrease substantially during the study period, about 40 percent more land would be irrigated at the end of the period because of the use of efficient irrigation

³Estimates of the total ground-water irrigated area affected by ground-water mining for these States were presented in table 2.

systems; and (3) net returns would decline from \$1.1 billion to \$0.5 billion from 1980 to 2020, but they would have been 50 percent less if efficient irrigation systems had not been adopted.

Hoyt's study in Arizona and California determined which crops and irrigation systems would offer the best opportunities for irrigators in ground-water mining areas. Hoyt included high, medium, and low crop prices in his analysis. With low crop prices, reduced production of barley and alfalfa in California and sorghum in Arizona could be expected; however, cotton in Arizona and California and wheat in California would continue to be grown, even with inefficient irrigation systems. Assuming high crop prices, all crops except sorghum would remain profitable, with only minor improvements in irrigation efficiency. The most profitable irrigation system conversions were the modified slope or level basin in Arizona and the modified slope or gated pipe systems in California.

Pfeiffer's study in Kansas also evaluated which crops and irrigation systems would be most profitable for irrigators in ground-water mining situations. With current prices, wheat could not be grown profitably with any system, nor could grain sorghum with any center pivot system, nor could alfalfa with the high-pressure center pivot system. However, other combinations of crops and irrigation systems were profitable. As irrigation costs rise and well yields decline, surge flow and low-pressure systems were the least-cost furrow and sprinkler systems and the most likely to be selected, depending on soil type and topography.

Both Hoyt and Pfeiffer concluded that small changes in commodity prices affected returns from irrigation more than did increased irrigation costs resulting from declining water levels. Thus, while they agreed that crops and irrigation systems would likely change over time as a result of ground-water mining, commodity prices would certainly play an important role in the rate of change.

Additional considerations were the rules and regulations imposed on irrigators in mining areas. Only 2 of the 11 States in this study, Arkansas and California, have placed no restrictions on ground-water use for irrigation. The other nine States exercise some control, and six have enacted legislation dealing directly with ground-water mining. The effect of the legislation in those six States has been to stop or sharply reduce irrigation expansion in mining areas. But the six States contain only 44 percent of the 14 million acres in ground-water mining areas. Furthermore, only 17 percent of the 36 million acres of land irrigated with ground water in the United States is subject to legislative restrictions on ground-water mining.

Ground-water mining will continue to be a problem in U.S. irrigated agriculture, and irrigators will have to adapt to changing water supplies and costs. But those changes will be gradual. The impact of ground-water mining is currently being felt in some regions, particularly in the Texas High Plains. The impact of ground-water mining nationally has been minimal because other areas irrigated with ground water have expanded irrigated acreage.

References

- (1) Ellis, John R., Ronald D. Lacewell, and Duane R. Reneau. *Estimated Impact of Irrigation Technology: Texas High Plains*. Texas A & M University, Department of Agricultural Economics, Oct. 1984.
- (2) High Plains Associates: Camp Dresser and McKee, Inc., Black and Veatch, and Arthur D. Little, Inc. *Six-State High Plains Ogallala Aquifer Regional Resources Study: Summary*. A report to the Department of Commerce and the High Plains Study Council, Austin, TX, July 1982.
- (3) Hoyt, Paul. "Producer Response to Declining Ground Water Levels in the Arid Southwest." Preliminary draft. U.S. Dept. of Agr., Econ. Res. Serv., July 1985.
- (4) Kromm, David E., and Stephen E. White. *Conserving the Ogallala: What Next?* Kansas State University-Manhattan, Department of Geography, 1985.
- (5) Pfeiffer, Robert. "Irrigator Response to Declining Ground Water Levels." Unpublished manuscript. U.S. Dept. of Agr., Econ. Res. Serv., July 1985.
- (6) Sloggett, Gordon R. *Energy and U.S. Agriculture: Irrigation Pumping, 1974-83*. AER-545. U.S. Dept. of Agr., Econ. Res. Serv., Dec. 1985.
- (7) _____. "Ground Water Management, Meeting the Challenge?" Speech prepared for the 1983 American Water Resources Association Meeting, San Antonio, TX, Oct. 1983.
- (8) _____. *Prospects for Ground Water Irrigation*. AER-478. U.S. Dept. of Agr., Econ. Res. Serv., 1981.
- (9) U.S. Department of Commerce, Bureau of the Census. *1982 Census of Agriculture*. Volume 1: *Geographic Area Series: State and County Data*, July 1982.

(10) Arizona

- (a) Denis, E.E. *Maps Showing Ground Water Conditions in the Harquahala Plains Area, Maricopa and Yuma Counties, Arizona, 1975*. Department of the Interior, U.S. Geological Survey, Tucson, AZ, 1976.
- (b) Hoyt, Paul, U.S. Dept. of Agr., Econ. Res. Serv., Tucson, AZ. Personal communication, 1985.
- (c) Long, M.R. *Maps Showing Ground Water Conditions in the Hassayampa Sub-Basin of the Phoenix Active Management Area, Maricopa and Yavapai Counties, Arizona, 1982*. Hydrologic Map Series Report 10. Department of Water Resources, Phoenix, AZ. June 1983.
- (d) Murphy, B.A., and J.D. Hadly. *Maps Showing Ground Water Conditions in the Upper Santa Cruz Basin Areas, Pima, Santa Cruz, Pinal and Cochise Counties, Arizona 1982*. Hydrologic Map Series 11. Department of Water Resources, Phoenix, AZ, Jan. 1984.
- (e) Wilson, R.P., and Natalie D. White. *Maps Showing Ground Water Conditions in the San-Simon Area, Cochise and Graham Counties, AZ and in Hidalgo County, NM 1975*. WRI 76-89. Department of the Interior, U.S. Geological Survey, Tucson, AZ, 1976.

(11) Arkansas

- (a) Edds, Joe. *Ground Water Levels in Arkansas, Spring 1984*. Open File Report 84-711. Department of the Interior, U.S. Geological Survey, Little Rock, AR, 1984.
- (b) _____, and Dan Fitzpatrick. *Maps Showing Altitude of the Potentiometric Surface and Changes in Water Levels in the Alluvial Aquifer in Eastern Arkansas, Spring 1983*. U.S. Geological Survey, Little Rock, AR, 1984.
- (c) Holland, Terrance W. *Use of Water in Arkansas, 1980*. Water Resources Summary Number 14. Arkansas Geological Commission, Little Rock, AR, 1981.
- (d) U.S. Department of Agriculture, Soil Conservation Service and Economic Research Service. *Arkansas Agricultural Water Use Study*. Arkansas Soil and Water Conservation Commission, Little Rock, AR, 1983.

(12) California

- (a) California Department of Water Resources. *Evaluation of Ground Water Resources: Sacramento Valley*. Bulletin 118-6. Sacramento, CA, Aug. 1978.
- (b) _____. *The Hydrologic-Economic Model of the San Joaquin Valley*. Bulletin 214. Sacramento, CA, Dec. 1982.
- (c) Erlewine, Terry L., California Department of Water Resources, Fresno, CA. Personal communication, Feb. 1985.

(13) Colorado

- (a) Borman, Ronald G. *Water Level Records for the Northern High Plains of Colorado, 1976-80*. Open File Report 80-438. Department of the Interior, U.S. Geological Survey, Lakewood, CO, 1980.
- (b) Miles, Don, Colorado State University Extension Service, Rocky Ford, CO. Personal communication, 1985.

(14) Florida

- (a) Healey, Henry G. *Potentiometric Surface of the Floridan Aquifer in Florida, May 1980*. Map Series 104. Department of the Interior, U.S. Geological Survey, Tallahassee, FL, 1982.
- (b) Mills, L.R., and C.P. Laughlin. *Potentiometric Surface of Floridan Aquifer, May 1975, and Change of Potentiometric Surface 1969-1975, Southwest Management District and Adjacent Areas*. WRI 76-80. Department of the Interior, U.S. Geological Survey, 1976.
- (c) Southwest Florida Water Management District. *Consumptive Water Use Information, 1984*. Brooksville, FL, 1985.

(15) Idaho

- (a) Anderson, Hal, and Paul M. Castelin, Idaho Department of Water Resources, Boise, ID. Personal communication, 1985.
- (b) Edwards, T.K., and H.W. Young. *Ground Water Conditions in the Cottonwood-West Oakley Fan Area, South Central Idaho*. WRI Report 84-4140. Department of the Interior, U.S. Geological Survey, Boise, ID, 1984.

- (c) Idaho Department of Water Resources. *Critical Ground Water Area Maps*. Undated working papers. Boise, ID.
- (d) Norton, M.A. *Ground Water Investigation of the Mountain Home Plateau, Idaho*. Idaho Department of Water Resources, Boise, ID. 1982.
- (e) Young, H.W., and R.F. Norvitch. *Ground Water Level Trends in Idaho, 1971-82*. Department of the Interior, U.S. Geological Survey, Boise, ID, 1984.
- (16) Kansas
- (a) Pabst, M.E., and B.J. Dague. *January 1984 Water Levels and Data Related to Water Level Changes in Western and South-Central Kansas*. Open-File Report 84-613. Department of the Interior, U.S. Geological Survey, Lawrence, KS, 1984.
- (b) Thomas, James G. *Engineering Newsletter—1982 Kansas Irrigation Survey*. Kansas State University Cooperative Extension Service, Manhattan, KS, 1983.
- (17) Nebraska
- (a) Johnson, Martin S., and Darryll T. Pederson. *Ground Water Levels in Nebraska, 1983*. NWSP 57. University of Nebraska-Lincoln, Institute of Agriculture and Natural Resources, Conservation and Survey Division, June 1984.
- (b) Natural Resources Commission, Data Bank. *Well Registration by County Through 1984*. Lincoln, NE, 1985.
- (c) University of Nebraska-Lincoln, Institute of Agriculture and Natural Resources, Conservation and Survey Division. *Map Location of Registered Irrigation Wells in Nebraska, 1984*. 1985.
- (18) New Mexico
- (a) Hudson, J.D., and R.L. Burton. *Ground Water Levels in New Mexico, 1978-1980*. Basic Data Report, New Mexico State Engineer, Santa Fe, NM, 1982.
- (b) Lansford, Robert R. *Sources of Irrigation Water and Irrigated and Dryland Acreages in New Mexico, by County, 1978-83*. Research Report 554. New Mexico State University-Las Cruces, Oct. 1984.
- (19) Oklahoma
- (a) Goemaat, Robert L. *Ground Water Levels in Observation Wells in Oklahoma, 1983-84 Climatic Years*. Open-File Report 85-87. Department of the Interior, U.S. Geological Survey, Oklahoma City, OK, 1985.
- (b) Schwab, Delbert. *1983 Irrigation Survey Oklahoma*. Oklahoma State University, Department of Agricultural Engineering, 1984.
- (20) Texas
- (a) Elder, Glenward R. *Records of Wells, Water Levels, Pumpage and Chemical Analysis of Water from the Carrizo Aquifer in the Winter Garden Area of Texas, 1970 Through 1977*. Report 254. Texas Department of Water Resources, Austin, Sept. 1980.
- (b) Gabrysch, R.K. *Ground Water Withdrawals and Changes in Water Levels in the Houston District, Texas 1975-79*. Report 286. Texas Department of Water Resources, Austin, Apr. 1984.
- (c) High Plains Water Conservation District Number 1. *The Cross Section*. Lubbock, TX, 1974-85.
- (d) Lockart, Carole. *Ground Water Resources of Colorado, Lavaca, and Wharton Counties, Texas*. Texas Department of Water Resources, Austin, July 1982.
- (e) North Plains Water Conservation District. *North Plains Water News*. Dumas, TX, 1968-1985.
- (f) Ratzlaff, Karl W. *Records of Wells, Drillers' Logs, Water Level Measurements and Chemical Analysis of Ground Water in Brazoria, Fort Bend, and Waller Counties, Texas, 1975-79*. Report 277. Texas Department of Water Resources, Austin, July 1983.
- (g) Rees, R., and W. Gushner. *Occurrence and Quality of Ground Water in the Edwards-Trinity Aquifer in the Trans-Pecos Region of Texas*. Report 255. Texas Department of Water Resources, Austin, Sept. 1980.
- (h) Texas Department of Water Resources. "Inventories of Irrigation in Texas, 1958-84." Preliminary report. Austin, 1985.

Appendix table 1—Crops grown in areas of ground-water decline, Arizona¹

County/ area	Alfalfa	Barley	Cotton	Sorghum	Wheat	Other	Total
	<i>1,000 acres</i>						
Cochise	4	0	6	19	18	17	64
Graham	4	4	3	12	3	0	26
Maricopa	83	24	98	21	61	18	305
Pima	0	0	12	5	8	0	25
Pinal	13	14	88	0	48	19	182
Yuma	0	0	4	0	0	0	4
Total	104	42	211	57	138	54	606

¹Basis for estimating area of decline was data supplied by Paul Hoyt, Econ. Res. Serv., U.S. Dept. of Agr., Tucson, AZ. Crop distribution data estimated from (9).

Source: (10).

Appendix table 2—Crops grown in areas of ground-water decline, Arkansas¹

County/ area	Cotton	Rice	Soybean	Other	Total
	<i>1,000 acres</i>				
Arkansas	0	25	32	3	60
Craighead	1	21	46	3	71
Cross	0	44	18	4	66
Lonoke	2	27	0	5	34
Poinsett	0	76	6	12	94
Prairie	0	29	20	2	51
Woodruff	0	39	10	0	49
Total	3	261	132	29	425

¹No new data were available on ground water decline since the previous decline study was completed. Crop distribution data were estimated from (9).

Source: (11).

Appendix table 3—Crops grown in areas of ground-water decline, California¹

County/ area	Alfalfa	Corn	Cotton	Grapes	Small grain	Other	Total
	<i>1,000 acres</i>						
Kern	53	7	195	18	31	73	377
Kings	33	12	133	3	66	54	301
Fresno	57	15	101	129	44	86	432
Madera	34	12	44	43	52	97	282
Merced	14	10	15	10	23	95	167
Stanislaus	0	1	0	4	5	15	25
Tulare	51	30	125	51	74	153	484
Total	242	87	613	258	295	573	2,068

¹Basis for area of decline estimates was data from the 1982 hydrologic-economic model of the San Joaquin Valley. Crop distribution was estimated from (9).

Source: (12).

Appendix table 4—Crops grown in areas of ground-water decline, Colorado¹

Area	Alfalfa	Corn	Beans	Grain sorghum	Wheat	Other	Total
	<i>1,000 acres</i>						
Northern High Plains	28	310	35	7	61	64	505
Southern High Plains	16	5	0	49	12	3	85
Total	44	315	35	56	73	67	590

¹Basis for area of decline was 1984 irrigated acreage data supplied by Donald Miles, Colorado State University. Crop distribution data were estimated with data from (9).

Source: (13).

Appendix table 5—Crops grown in areas of ground-water decline, Florida¹

Area	Citrus	Pasture	Vegetables	Other	Total
	<i>1,000 acres</i>				
Southwest Florida Management District	200	20	20	10	250

¹Data from the Southwest Florida Management District indicate no significant change in the decline area from the previous decline study (8). Crop distribution data were estimated from (9).

Source: (14).

Appendix table 6—Crops grown in areas of ground-water decline, Idaho¹

County/area	Alfalfa	Barley	Potatoes	Sugar beets	Wheat	Other	Total
	<i>1,000 acres</i>						
Cassia	39	30	2	16	63	38	188
Elmore	0	0	1	0	1	2	4
Oneida	11	6	0	0	3	1	21
Twin Falls	2	1	0	0	2	5	10
Total	52	37	3	16	69	46	223

¹Basis for estimating area of decline was data from several sources and personal communication (see (15)). Crop distribution data were estimated from (9).

Source: (15).

Appendix table 7—Crops grown in areas of ground-water decline, Kansas¹

Area	Alfalfa	Corn	Grain sorghum	Wheat	Other	Total
	<i>1,000 acres</i>					
Northwest	21	181	73	91	45	411
West Central	9	41	71	82	24	227
Southwest	92	442	398	510	100	1,542
Total	122	664	542	683	169	2,180

¹Basis for estimating area of decline was the 1982 report on the Ogallala High Plains Aquifer (2). Crop distribution data were estimated from (9).

Source: (16).

Appendix table 8—Crops grown in areas of ground-water decline, Nebraska¹

Area	Alfalfa	Corn	Grain sorghum	Wheat	Other	Total
<i>1,000 acres</i>						
Southeast	15	816	67	7	212	1,117
East South Central	13	297	5	1	26	342
Southwest	15	210	5	25	48	303
West Central	4	7	0	0	16	27
Northwest	6	22	0	11	48	87
East Central	4	23	1	0	2	30
Northeast	7	81	45	0	0	133
Total	64	1,456	123	44	352	2,039

¹Bases for estimating area of decline were 1984 irrigation well registration data and the 1984 well location map. Crop distribution data were estimated from (9).

Source: (17).

Appendix table 9—Crops grown in areas of ground-water decline, New Mexico¹

County/area	Alfalfa	Cotton	Corn	Grain sorghum	Wheat	Other	Total
<i>1,000 acres</i>							
Chaves, Eddy	84	21	1	4	7	13	130
Curry, Lea, Roosevelt	37	26	49	81	114	43	350
Luna	3	25	1	11	4	11	55
Torrance	12	0	4	0	1	8	25
Total	136	72	55	96	126	75	560

¹Data from the annual New Mexico irrigation survey show no significant change in irrigated acreage since the last ground-water decline study (18). Crop distribution data were estimated from (9).

Source: (18).

Appendix table 10—Crops grown in areas of ground-water decline, Oklahoma

County/area	Alfalfa	Cotton	Corn	Grain sorghum	Peanuts	Wheat	Other	Total
<i>1,000 acres</i>								
Caddo	17	4	2	13	26	9	13	84
Harmon	3	13	0	1	0	6	1	24
Texas, Beaver, Cimarron	17	0	29	167	0	198	4	415
Total	37	17	31	181	26	213	18	523

¹Basis for area of decline was the 1983 Oklahoma irrigation survey. Crop distribution data were estimated from (9).

Source: (19).

Appendix table 11—Crops grown in areas of ground-water decline, Texas¹

Area	Hay and alfalfa	Cotton	Corn	Grain sorghum	Peanuts	Rice	Soybeans	Wheat	Other	Total
<i>1,000 acres</i>										
Northern High Plains	15	0	135	384	0	0	9	507	40	1,090
Southern High Plains	32	1,070	420	624	25	0	315	517	158	3,161
Trans-Pecos	19	9	0	2	0	0	0	1	21	52
Winter Garden	48	28	11	6	0	0	0	4	17	114
Gulf Coast	1	1	2	3	0	133	0	0	8	148
Total	115	1,108	568	1,019	25	133	324	1,029	244	4,565

¹Basis for the area of decline was the 1984 Texas irrigation survey. Crop distribution was estimated from (9).

Source: (20).

Appendix table 12—Size and characteristics of ground-water decline areas, Arizona

County/area	Decline area irrigated	Lift	Average annual decline
	<i>1,000 acres</i>	<i>-----Feet-----</i>	
Cochise	64	375	2.5
Graham	26	75	2.0
Maricopa	305	275	3.0
Pima	25	350	3.0
Pinal	182	535	3.0
Yuma	4	375	2.0
Total	606	N/A	N/A

N/A = Not applicable.
Source: (10).

Appendix table 13—Size and characteristics of ground-water decline areas, Arkansas

County/area	Decline area irrigated	Lift	Average annual decline
	<i>1,000 acres</i>	<i>-----Feet-----</i>	
Arkansas	60	120	1.3
Craighead	71	70	1.0
Cross	66	115	.8
Lonoke	34	80	1.0
Poinsett	94	80	1.0
Prairie	51	115	1.3
Woodruff	49	50	.5
Total	425	N/A	N/A

N/A = Not applicable.
Source: (11).

Appendix table 14—Size and characteristics of ground-water decline areas, California

County/area	Decline area irrigated	Lift	Average annual decline
	<i>1,000 acres</i>	<i>-----Feet-----</i>	
Kern	377	260	3.5
Kings	301	165	.8
Fresno	432	110	2.5
Madera	282	135	1.3
Merced	167	110	1.8
Stanislaus	25	100	.5
Tulare	484	185	1.0
Total	2,068	N/A	N/A

N/A = Not applicable.
Source: (12).

Appendix table 15—Size and characteristics of ground-water decline areas, Colorado

Area	Decline area irrigated	Lift	Average annual decline
	<i>1,000 acres</i>	<i>-----Feet-----</i>	
Northern High Plains	505	175	2
Southern High Plains	85	275	2
Total	590	N/A	N/A

N/A = Not applicable.
Source: (13).

Appendix table 16—Size and characteristics of ground-water decline areas, Florida

Area	Decline area irrigated	Lift	Average annual decline
	<i>1,000 acres</i>	<i>-----Feet-----</i>	
Southwest Florida Management District	250	100	2.5

Source: (14).

Appendix table 17—Size and characteristics of ground-water decline areas, Idaho

County/area	Decline area irrigated	Lift	Average annual decline
	<i>1,000 acres</i>	<i>-----Feet-----</i>	
Cassia	188	200	2.8
Elmore	4	350	5.0
Oneida	21	250	3.0
Twin Falls	10	375	1.1
Total	223	N/A	N/A

N/A = Not applicable.
Source: (15).

Appendix table 18—Size and characteristics of ground-water decline areas, Kansas

Area	Decline area irrigated	Lift	Average annual decline
	<i>1,000 acres</i>	----- <i>Feet</i> -----	
Northwest	411	200	1.0
West Central	227	190	2.5
Southwest	1,542	275	4.0
Total	2,180	N/A	N/A

N/A = Not applicable.
Source: (16).

Appendix table 20—Size and characteristics of ground-water decline areas, New Mexico

County/area	Decline area irrigated	Lift	Average annual decline
	<i>1,000 acres</i>	----- <i>Feet</i> -----	
Chaves, Eddy	130	160	2.5
Curry, Lea, Roosevelt	350	200	2.0
Luna	55	100	1.0
Torrance	25	100	1.0
Total	560	N/A	N/A

N/A = Not applicable.
Source: (18).

Appendix table 19—Size and characteristics of ground-water decline areas, Nebraska

Area	Decline area irrigated	Lift	Average annual decline
	<i>1,000 acres</i>	----- <i>Feet</i> -----	
Southeast	1,117	100	0.5
East South Central	342	25	.5
Southwest	303	150	1.2
West Central	27	250	2.0
Northwest	87	100	1.0
East Central	30	125	1.0
Northeast	133	50	1.0
Total	2,039	N/A	N/A

N/A = Not applicable.
Source: (17).

Appendix table 21—Size and characteristics of ground-water decline areas, Oklahoma

County/area	Decline area irrigated	Lift	Average annual decline
	<i>1,000 acres</i>	----- <i>Feet</i> -----	
Caddo	84	100	1.0
Harmon	24	100	2.5
Texas, Beaver, Cimarron	415	275	2.0
Total	523	N/A	N/A

N/A = Not applicable.
Source: (19).

Appendix table 22—Size and characteristics of ground-water decline areas, Texas

Area	Decline area irrigated	Lift	Average annual decline
	<i>1,000 acres</i>	----- <i>Feet</i> -----	
Northern High Plains	1,090	275	2.0
Southern High Plains	3,161	175	1.25
Trans-Pecos	52	200	4.0
Winter Garden	114	175	4.0
Gulf Coast	148	75	1.0
Total	4,565	N/A	N/A

N/A = Not applicable.
Source: (20).