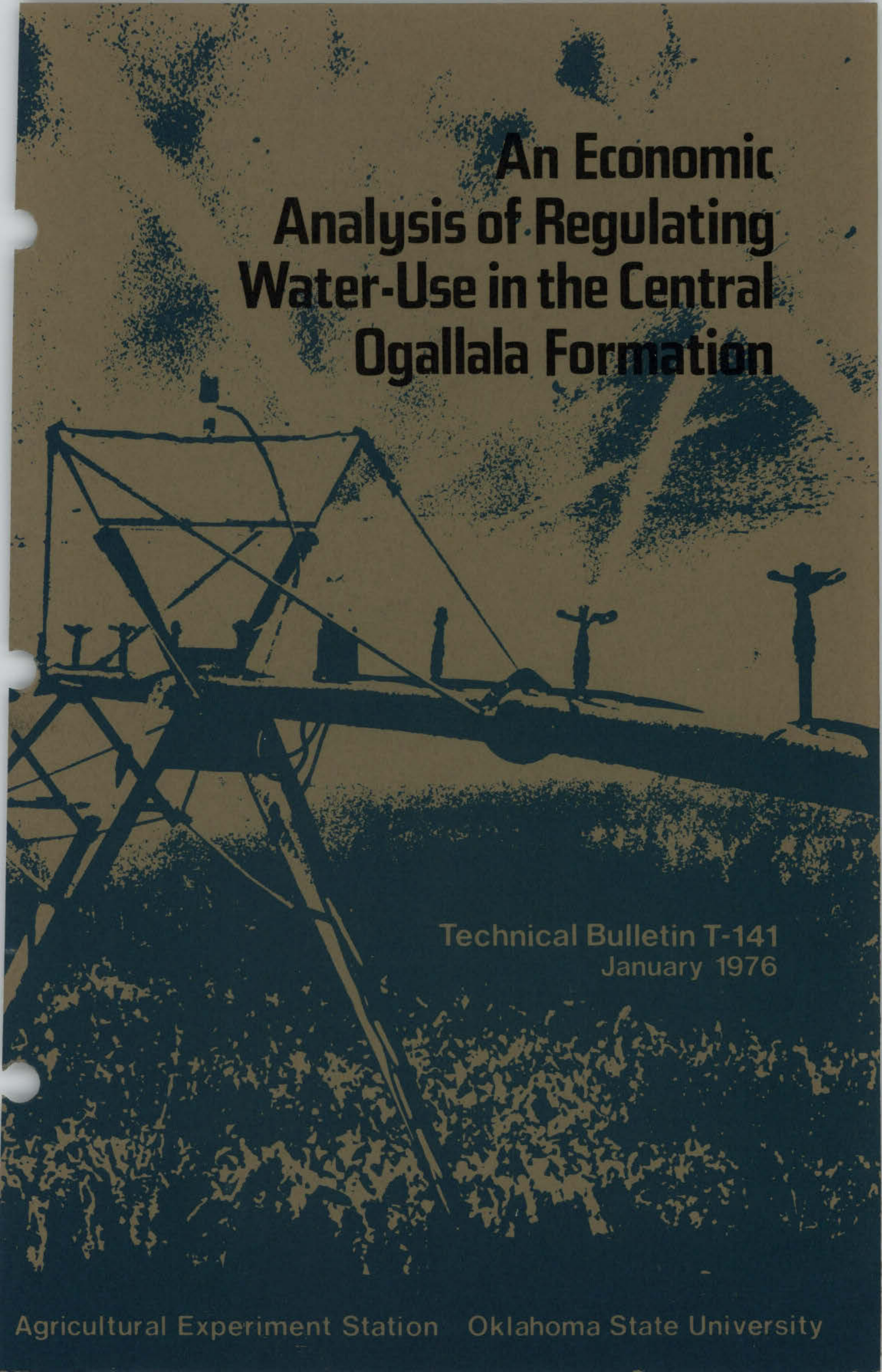
An Economic Analysis of Regulating Water-Use in the Central Ogallala Formation



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Abstract

The Central Basin of the Ogallala Formation is essentially a closed container of water. Average annual recharge is negligible relative to current withdrawals. Thus, over time, the quantity of water within the Central Basin is being depleted by the actions of individual irrigators. Eventually, as the water table declines and per unit pumping costs rise, it will become uneconomical to pump water for irrigation purposes in some parts of the Central Basin. The purpose of this study was to evaluate the effects of several specific methods of regulating water use on farms in the Central Basin on net farm income, variability of net farm income, net worth, variability of net worth, quantity of water pumped and the present value of the streams of net income.

A firm-level simulation model is used to simulate the effects of unrestricted pumping, a quantity limitation and a graduated tax on water pumped above the quantity limitation on representative farms in each of two water resource situations. Wheat, grain sorghum and corn yields are determined endogeneously as a function of soil moisture and atmospheric stress during critical stages of plant development. A general irrigation strategy followed by many of the better irrigators in the study area is simulated over a 20-year period and replicated 15 times.

Results indicate, for the "poor water" resource situation, that total water use over the 20-year period is about the same under the three regulatory alternatives considered. Mean net farm income under the graduated tax alternative is significantly above mean net farm income under unrestricted pumping and a quantity limitation. This result occurs because the taxed irrigator achieves more timely irrigaton in relation to plant needs. Since pumping costs rise more slowly, net returns per acre and net farm income are higher despite the tax payment. In the "adequate water" resource situation, unrestricted pumping results in the greatest level of water use and the highest net farm income.

Policy implications differ somewhat for the two resource situations. In the "poor water" situation economic exhaustion appears likely in about 20 years regardless of the water-use policy adopted. Nevertheless, irrigators need to be shown that application

of economic decision rules in allocating water to maximize net returns, rather than crop yields, can increase the economic life of the aquifer and lead to higher net farm income.

Economic exhaustion of the "adequate water" portion of the aquifer is likely to occur far enough in the future that policy makers may find it difficult to make a convincing case for water-use regulation.

An Economic Analysis of Regulating Water-Use in the Central Ogallala Formation

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Introduction

The Ogallala Formation is a major unconsolidated aquifer underlying most of the Great Plains. This study is concerned with water use in the central part of the Ogallala Formation which is bounded on the north by the Arkansas River in Kansas and on the south by the Canadian River in Texas. Some portions of the central area are underlain by other formations (e.g., the Dakota and Cheyenne sandstones on the west) which also provide water for users living in the area.

Some portions of the Central Ogallala are very thin (such as the extreme eastern parts) and are not capable of supplying large quantities of water. Thus, the boundaries of the study area were limited to those portions of the Central Ogallala that (1) represent either large actual or potential water use for irrigation and (2) that obtain their water supply primarily from the Ogallala Formation. The boundaries of the study area are shown in Figure 1. The part of the Central Ogallala considered in this project includes a portion of two counties in southeastern Colorado, eight counties in southwestern Kansas, the three Panhandle counties of Oklahoma, and eight counties in the northern part of the Texas High Plains. The land area overlying this hydrologic subdivision is approximately 17,500 square miles.

Agriculture is the major primary industry upon which the economy of the study area is dependent. The production of wheat,

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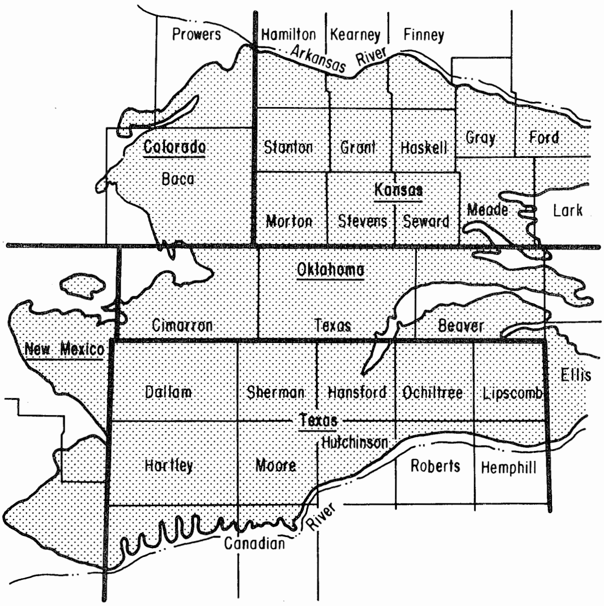

Figure 1. The Study Area

grain sorghum and beef cattle dominates the agricultural sector of the economy. It appears the region will continue to produce feed grains, food grains and beef. In the census year 1964, wheat and sorghum accounted for 92.1 percent of the total irrigated acreage of the eight main irrigated crops in the area and 98.6 percent of the total dryland acreage of the eight crops [6, p. 185]. Since that time, irrigated corn has continued to increase in importance. In 1974, irrigated corn for grain and silage represented more than a quarter of total irrigated acreage in the Oklahoma Panhandle counties.

The area overlying the Central Ogallala, once a large feed grain surplus area, currently consumes as much feed grain as produced in the average year. This area is expected to have continued growth in the cattle feeding industry. This growth is expected to provide a market for the feed grains and forages produced in the area from an expanded irrigated acreage [84].

Irrigation wells to tap the Central Ogallala Formation were drilled as early as 1932, but the greatest development has occurred since 1950. The advent of large economical and efficient pumping systems coupled with the severe drought of 1952-56 accelerated the growth of irrigation. The portion of the study area in Texas experienced the most rapid growth in irrigation both in absolute and relative terms followed by Oklahoma, Kansas and Colorado in that order. The breakdown of irrigation development for the period 1950-1965 by state is given in Table 1. During the 1950-65 period the number of irrigated acres increased from 17,000 to 1,003,000 in Texas, from 10,000 to 117,000 in Oklahoma, from 34,000 to 279,000 in Kansas and from 9,000 to 29,000 in Colorado. By 1965, 13.7 percent of the total study area was irrigated. Between 1965 and 1974, irrigated acreage in the Oklahoma Panhandle counties increased to approximately 300,000 acres.

The net volume of water withdrawn from the Central Ogallala Formation has continued to increase with the expansion of irrigation. While average annual recharge is estimated to be about .27 million acre feet [6, p. 193], the annual withdrawal of water from the aquifer in recent years has exceeded two million acre feet. As shown in the last column of Table 1, the first overdraft of the aquifer occurred around 1954 when a net of 113,650 acre feet of water was pumped. By 1965 the overdraft had increased to over 2.7 million acre feet per year and currently exceeds 3 million acre feet per year. The amount of water withdrawn for irrigation is expected to increase anually during the next several years. This implies the rate of annual overdraft will be even greater in the future.

The consequence of continued overdraft of the aquifer is a reduction in thickness of the water-saturated material and an increase in the pump lift, thereby increasing the per-unit cost of recovering water from the aquifer. Several studies of the average annual decline in the static water level have been reported in various areas of the Central Basin of the Ogallala Formation [9, pp. 41-49 and 28, pp. 14-32]. These studies indicate the average annual decline in most counties has exceeded two feet since 1963. More recent data reflects declines averaging nearly three feet per year during the 1966-75 period and estimates the 1974-75 decline as exceeding 3.6 feet. Continued overdraft is expected to result in significant declines throughout the entire study area.

The Problem

Developments of the past decade clearly indicate that further decline in the water table and the quantity of water in storage in the Central Ogallala Formation will occur over time. As the water table declines the unit cost of pumping water increases. *Ceteris paribus*,

Table 1. Estimated Number of Irrigated Acres and Acre Feet of Ground Water Applied in the Study Area 1950-1965 [a]

Year	Colorado		Kansas		Oklahoma		Texas		Total		Year to Year Change in Total		
	Irrigated Acres	Acre Feet Withdrawn	Irrigated Acres	Acre Feet Withdrawn	Irrigated Acres	Acre Feet Withdrawn	Irrigated Acres	Acre Feet Withdrawn	Irrigated Acres	Acre Feet Withdrawn	Irrigated Acres	Acre Feet Withdrawn	Net Withdrawal [b]
1950	8,584	14,593	34,012	57,820	10,024	17,041	16,944	28,805	69,564	118,259	11,203	23,084	-151,819
1951	9,027	15,797	42,085	73,649	10,458	18,302	19,197	33,595	80,767	141,343	16,193	46,758	-128,735
1952	9,470	18,372	53,376	103,549	10,892	21,130	23,222	45,050	96,960	188,101	32,214	70,247	-81,977
1953	9,913	19,826	67,120	134,240	16,985	33,970	35,156	70,312	129,174	258,348	64,626	125,376	-11,730
1954	10,356	20,505	86,904	172,070	23,078	45,694	73,462	145,455	193,800	383,724	110,109	254,486	113,646
1955	12,097	25,404	135,745	285,065	35,478	74,504	120,589	253,237	303,909	638,210	196,716	618,358	368,132
1956	13,838	34,733	150,942	378,942	64,456	161,785	271,389	681,186	500,625	1,256,568	119,379	14,440	986,490
1957	15,580	31,939	235,693	483,171	69,124	141,704	299,607	614,194	620,004	1,271,008	13,941	-167,943	1,000,093
1958	16,213	28,211	249,573	434,257	61,567	107,127	306,592	533,470	633,945	1,103,065	28,337	29,437	832,987
1959	16,846	28,807	256,409	438,459	63,280	108,209	325,747	557,027	662,282	1,132,502	39,439	60,424	862,424
1960	18,940	32,198	270,670	460,139	63,390	107,763	348,721	592,826	701,721	1,192,926	29,356	93,770	922,848
1961	21,034	37,020	279,516	491,948	63,500	111,760	367,027	645,968	731,077	1,286,696	64,462	153,230	1,016,618
1962	23,128	41,862	299,865	542,756	63,609	115,132	408,937	740,176	795,539	1,439,926	188,937	588,937	1,169,848
1963	25,222	51,957	322,176	663,683	73,962	152,362	563,116	1,160,018	984,476	2,028,020	297,428	958,817	1,749,942
1964	27,314	63,642	347,999	810,838	95,443	222,382	811,148	1,889,975	1,281,904	2,986,837	246,885	-663,078	2,708,759
1965	29,406	44,697	379,248	576,457	116,925	177,726	1,003,210	1,524,879	1,528,789	2,323,759			

[a] Estimated rate of water application taken from "**Ground Water in the Cimarron River Basin**", 1966, prepared by the U.S. Geologic Survey Water Resource Division for the U.S. Corps of Engineers, Tulsa District, p. 33.

[b] Acre feet applied minus recharge. Negative figures indicate a net addition to storage.

net returns per acre irrigated will decrease as time proceeds. Eventually it will be uneconomical to pump water for irrigation purposes in some parts of the study area. This implies resources once committed to irrigated production will have to revert to dryland farming.

The adjustment from irrigation to dryland farming will result in serious primary and secondary reductions of income in the study area. Primary reduction of income entails the higher net returns per acre of production foregone and some of the resources abandoned in switching to dryland farming. The secondary reduction involves the losses attributed to reduced land prices, and the economic slump created through the multiplier effect by the reduction of demand for inputs and services that compliment irrigated crop production in the study area. How severe the adjustments to the declining water table will be is, in part, determined by how fast the ground water is depleted and, in part, by the actions taken to lessen its adverse affects.

In portions of the study area characterized as poor water situations (saturated thicknesses of 100 feet or less) the effects of further declines in saturated thickness will have an immediate and significant impact on well yields and pumping costs. Continued expansion will likely lead to economic exhaustion of the water supply in these areas within the next 20 years. Irrigators in adequate water situations (saturated thicknesses average 325 feet) may continue to pump for an extended period without significantly reducing well yields or increasing irrigation costs. Due to the irregularities of the Ogallala Formation, effects of the declining water supply will not be uniformly distributed among either individual irrigators or economic areas within the study area.

Objectives

This bulletin outlines some potential methods for limiting water use in the study area and present a detailed evaluation of several of the specific measures discussed. More specifically, the objectives of the study are:

(1) To define several specific methods of regulating water use on farms in the Central Basin of the Ogallala Formation,
(2) To simulate, for poor and adequate water resource situations, over a 20-year period, each method of regulating water use,
(3) To compare the effects of the methods of water-use

regulation on net farm income, variability of net farm income, net worth, variability of net worth, quantity of water pumped and availability of water for future periods.

(4) To evaluate the alternative methods of restraining water use by discounting the streams of net returns and comparing the present values of those net income streams.

Methods of Regulating Water Use

Private and Social Benefits

From a public viewpoint, the maximization of long-run social benefits from the use of water represents the dominant goal of water resource use [112, p. 1248]. This goal can be accomplished by efficient allocation of water among competing uses in present and future time periods. In the present period, efficient allocation between two competing uses, as production and consumption, occurs when the marginal rate of substitution in production of alternative commodities equals the marginal rate of substitution in consumption of the same commodities.

In allocating a scarce resource, such as water, for the production of two commodities, equilibrium occurs where the production possibilities curve for water in production of two commodities is just tangent to society's indifference curve for those two commodities and both curves are tangent to the price ratio line which reflects consumers' desires. The resulting allocation implies that the marginal value product of the resource is equal in all of its uses. Alternative resource allocations would not enable society to reach a higher indifference curve.

Derivation of conditions for optimal resource allocation under static assumptions represents the simplest application of economic concepts to the water allocation problem. As long as the quantity of water available for pumping from an underground aquifer greatly exceeds demand, problems of common usage and timing of water usage do not arise. However, the central basin of the Ogallala Formation contains a finite quantity of water. Average annual recharge is negligible. Irrigators pumping from the central basin are essentially engaged in a water mining operation. Thus, the problem is complicated by both the introduction of time and the theoretical and practical complexities of utilizing a stock resource with commonality properties.

A stock resource is one whose total quantity does not increase significantly with time. In fact, each rate of use diminishes some future rate of use [58, p. 1112]. Water in the central basin of the Ogallala Formation may be classified as a stock resource possessing many of the characteristics of commonality.[1] That is, all irrigators draw from the common source and each has his own self-interests in mind. The present institutional framework fails to provide an individual the right to "save" a portion of his water in the current period for use in future periods. The Doctrine of Prior Appropriation insures the irrigator the right to put a specified number of acre feet of water per year to beneficial use. Failure to put the entire amount allocated to beneficial use within five years results in a reduction in water rights to the amount actually being put to beneficial use [89, p. 14]. Thus, irrigators are encouraged by current water law to act as if the value of water, while in the underground aquifer, is zero. Each irrigator acts to maximize returns to the scarce water resource from year to year without reference to future years. For all irrigators as a group, their collective actions increase future pumping costs and reduce the availability of future water supplies.

The problem of commonality of water use leads to "spill-over" costs arising from two sources [67, pp. 428-249]. The first of these arises when all the costs of extra pumping are not borne by the individual irrigator, but fall upon other pumpers in the basin and society in general. The second type of spill-over cost results when one irrigator pumps sufficient water to lower the water table, reduce well yields and increase pumping costs. The increased cost of pumping must eventually be borne partly by all irrigators pumping from the basin. The first of these costs arises because the individual irrigator, without water rights which are valid in future periods, has no incentive to maximize the present value of water use over time. The second arises because irrigators continue to irrigate as long as the current marginal value productivity of the water resource exceeds the variable costs of pumping and delivering water to plants in the current period.

These "spill-over" costs result in a divergence of private and social costs. The difference in optimal water allocations caused by the divergence of private and social costs is illustrated in Figure 2. The marginal social cost curve (MSC) lies above the marginal private

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1. For a more complete discussion of the economics of commonality see H.S. Gordon, "The Economic Theory of a Common-Property Resource: The Fishery," **The Journal of Political Economy**, Vol. 42, No. 2 (1954), pp. 124-142; J. Hirshleifer, et al., **Water Supply: Economics, Technology and Policy**, (Chicago, 1960), pp. 59-73; and J.W. Milliman, "Commonality, the Price System and Use of Water Supplies," **The Southern Economic Journal**, Vol. 22, No. 4 (1956), pp. 426-437.

cost curve (MPC). The marginal value product curve (MVP) represents the value of water in use. The individual irrigator in seeking to optimally allocate his water resources considers only marginal private costs. Thus, the optimal allocation of water resources for the individual occurs where the MPC of pumping the incremental unit of water equals the MVP of that unit of water, or at point D in Figure 2. Each individual pumps OB acre feet of irrigation water.

The socially optimal allocation of water results only when marginal social costs are considered in the allocative process. If private and social costs were included, each producer would equate MSC and MVP (point C in Figure 2) with the socially optimal allocation of water being OA acre feet. Thus, if the individual producer does not consider the full social and private cost of irrigation water used in production, water usage is expanded beyond the socially optimal levels by an amount equal to AB.

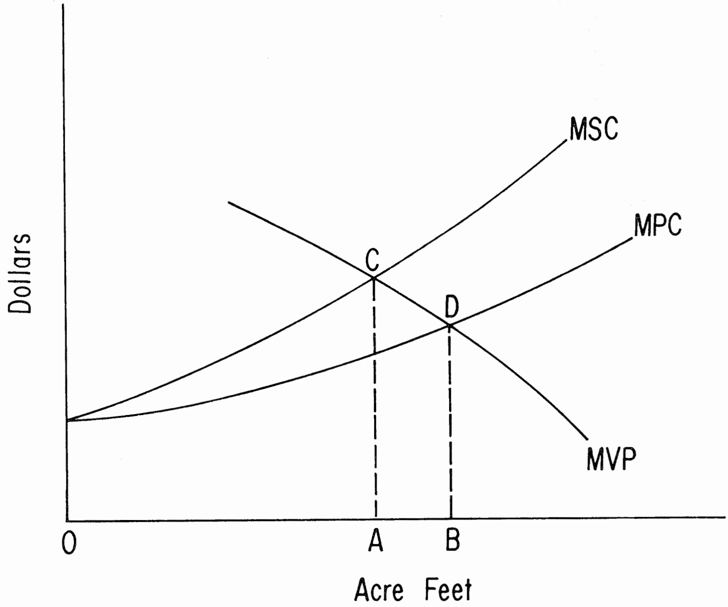

Figure 2. Illustration of the Divergence of Private and Social Costs and the Resulting Resource Allocations

The "No Policy" Alternative

The course of action currently being followed in the study area is to do nothing except record water rights and require well spacing to avoid obvious short-run conflicts. A policy of this type has been the general course followed by many states until the situation developed into a critical problem [56, p. 33].

The absence of water-use regulation is one alternative analyzed. Under this alternative each farmer can withdraw the amount of water desired, limited only by the water resource situation, his pumping capacity and the profitability of withdrawing water. The only institutional restraints imposed on the farmer in addition to filing for water rights is that the wells be located at least the specified distance from his neighbors irrigation wells. This approach allows irrigators to base their water use decisions on private costs, paying little if any attention to the social costs.

Several institutional alternatives appear capable of more closely aligning marginal private and marginal social costs. The two considered in this study are limiting the quantity of irrigation water each irrigator is allowed to pump during each crop year and placing a tax per acre inch on a portion of the irrigation water pumped during each crop year.

The Quantity Restriction

The effects of a quantity limitation on the divergence of private and social costs are depicted in Figure 3. By limiting pumping to OA acre feet per year, the objective of forcing alignment of MSC and MVP is achieved and a socially optimal allocation of water results.

Theoretically, limiting water use to socially optimal levels through the use of a quantity limitation is sound. From a practical standpoint, several problems arise. First, a quantity limitation works best when annual recharge is large relative to water use. The limitation can be set to a "safe yield" for the aquifer and socially optimal resource allocations achieved. However, if recharge is negligible relative to current water usage, and such is the case in the study area, limitation of water use to a safe yield, or to the amount of average annual recharge, would not be economic.

A more realistic quantity limitation might be OB acre feet per year in Figure 3. If the irrigator is forced to observe the quantity restriction, with the alternative being a severe penalty on the form

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2. The Oklahoma Water Resources Board has the power to order proper spacing of wells to insure an orderly withdrawal of water in relation to average annual recharge. It can also require metering of wells to record amounts pumped and can requirè persons to cease excessive withdrawals in reverse order of their water rights. It is empowered to restrict the rate of water use to one cubic foot of water per second for each seventy acres, or equivalent thereof, delivered on the land, for a specified time in each year [89, p. 15]. By not indicating the intended length of "a specified time in each year," water use may be restricted to any amount desired by the Water Resources Board.

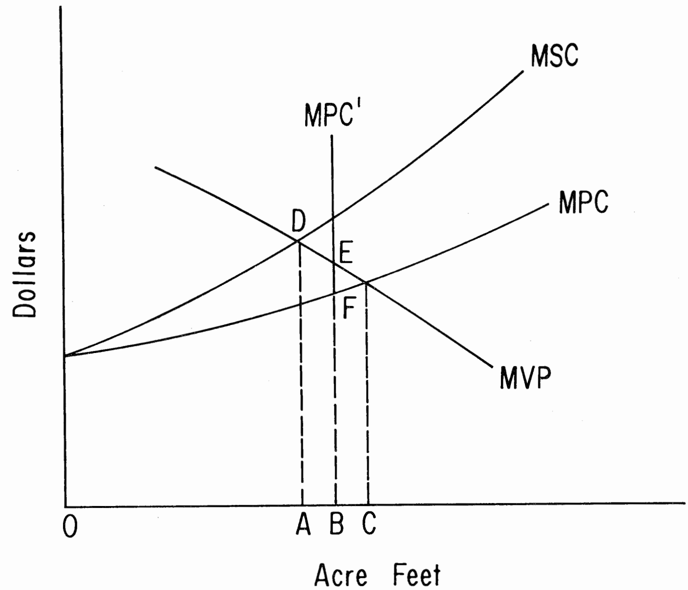

Figure 3. The Effect of a Quantity Limitation on Divergence of Private and Social Costs and Resource Allocation

of a fine or assessment, he will consider only marginal private costs out to OB acre feet of irrigation water per year. Then, the marginal private cost curve becomes vertical. At point F, the MVP of additional irrigation water exceeds the MPC of that water. However, a fine or assessment equal to or greater than EF will provide sufficient incentive for the irrigator to consider marginal private cost curve MPC' and restrict pumping to OB acre feet per year. Water use is greater than the socially optimal level of OA acre feet per year, but less than OC acre feet per year under unrestricted pumping.

Ideally, the effect of limiting the quantity of water withdrawn to each of several levels in the OA to OC range should be evaluated. Only one level of quantity restriction is analyzed, because the cost of completing the analysis for multiple levels exceeded the funds available.

The quantity selected is 1.5 acre feet per acre of water rights. This level was selected because it would require a significant reduction in pumping, approximately 25 percent of the current level, and because it has been suggested as an alternative by others dealing with the overdraft problem in the area [56, p. 32]. The quantity limitations, which could be handled within the existing legal and institutional framework of the study area, is the second alternative analyzed.

Imposing a Graduated Tax

The effects of imposing a tax per unit of irrigation water pumped on the divergence of private and social costs and resource allocation is shown in Figure 4. A per unit tax on each acre foot of irrigation water pumped shifts the marginal private cost (MPC) curve upward. If the tax is a constant rate per unit equal to HK in Figure 4, the new marginal private cost curve (MPC') is parallel to and above the old MPC curve. Rather than pumping OC acre feet per year, the individual irrigator equates MVP and MPC', reducing the number of acre feet pumped to OB. However, OB acre feet exceeds the socially optimal OA acre feet by an amount equal to AB. By raising the constant tax rate to DE dollars per acre foot, the producer considers the full private and social costs of pumping irrigation water. The tax rate DE per unit shifts the MPC curve upward to MPC". This tax rate induces the producer to equate MVP and MPC", and utilize the socially optimal OA acre feet of irrigation water.

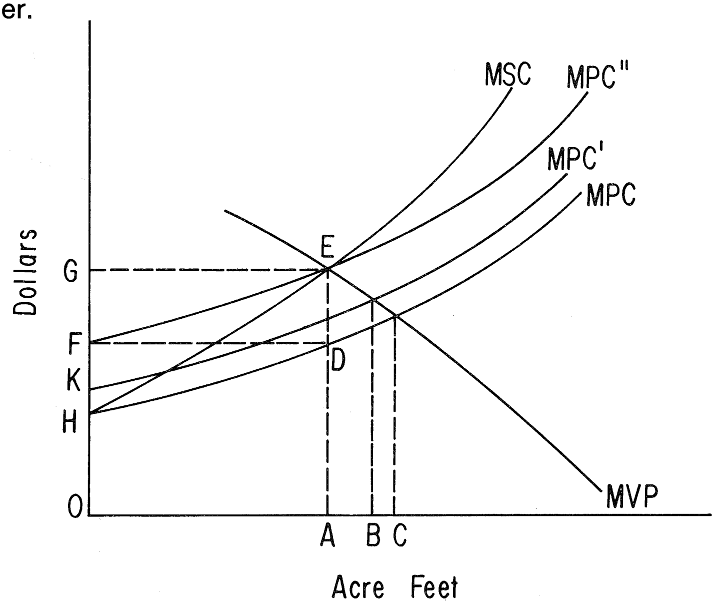

Figure 4. Illustration of the Effects of Alternative Tax Measures on the Divergence of Private and Social Costs and Resource Allocation

A per unit tax of DE would generate revenue for the controlling agency equal to the rectangle FGED. The excess of social over private cost is only HED. Revenue generated exceeds the divergence of private and social costs when the tax rate is DE per unit. Several alternatives exist to utilize the revenue. One is to return a portion of the revenue collected to pumpers as a bonus unrelated to the quantity of water pumped. This approach would involve an income transfer from the larger to the smaller pumpers. A second atlernative is to return a portion of the revenue to pumpers with payments being inversely related to the quantity pumped. This method of payment provides an incentive to reduce pumping.

The optimal per unit tax for all water users is not the constant DE per unit of water pumped. This tax rate is optimal only for the marginal unit at OA acre feet. For units less than OA acre feet, the optimal rate would be a graduated tax which, for any point between O and A, equates MPC and MSC [67, p. 434].

A slightly different approach to taxing water use is taken in this study. No attempt was made to impose a tax of sufficient magnitude to align MPC and MVP at the socially optimal level of water use. Instead, the individual irrigator is allowed to pump without taxation until a quantity limitation, such as the limitation discussed in Figure 3, is reached. Once the quantity limitation is attained, additional water is pumped only if the irrigator is willing to pay a substantial tax on each unit of water pumped above the quantity limitation. This situation is presented graphically in Figure 5. Quantity OA represents the socially optimal allocation of the water resource at the point where MVP equals MSC. Quantity OD represents the optimal allocation of water by the individual producer who considers only private costs in equating MVP and MPC. Quantity OB represents the number of units of water pumped by an individual irrigator under the quantity restriction depicted in Figure 3. Assume that once OB units have been pumped, the irrigator must pay a per unit tax equal to EF on the marginal unit pumped above OB units. In effect the irrigator must now consider marginal private cost curve MPC'. At OB units of water pumped, MPC' is less than MVP. The economically rational producer will expand water use to OC units where MPC' equals MVP.

Both OB and OC are less than quantity OD pumped without restrictions, but both exceed the socially optimal rate of OA acre feet per year. Thus, neither the quantity restriction nor graduated per unit tax considered here will successfully force a socially optimal alloction of irrigation water. However, from society's standpoint, both are to be preferred over unrestricted pumping

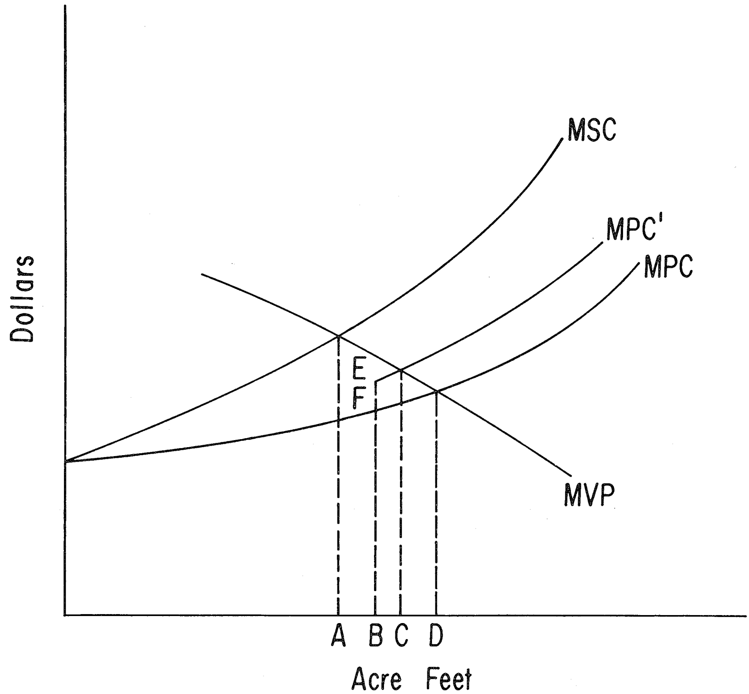

Figure 5. The Effect of a Graduated Tax per Unit Pumped Above a Quantity Limitation on Divergence of Private and Social Costs and Resource Allocation

because both reduce the divergence of private and social costs.

The third alternative evaluated in this analysis is the imposition of a per unit tax on each acre inch of water pumped above the quantity limitation discussed as the second alternative. The tax rate selected of $.50 per acre inch is modest, but projected to be large enough to significantly reduce water use. Under this alternative the quantity of water pumped per crop year is restricted to 1.5 acre feet per acre of water rights, but allowing the irrigator to apply additional irrigation water of a tax of $.50 per acre inch is paid for each acre inch pumped above the quantity limitation.

Taxing water does not fit within the current social or institutional structure of the study area. However, there is ample authority for the imposition of taxes on water uses [91, p. 276]. The mechanism for establishing a tax rate and administering it must be established by the respective water resource boards. The imposition of a tax is analyzed in this study because it seems to be a feasible alternative and one that provides an economic incentive to conserve water use.

Additional Considerations

An evaluation of the three alternatives specified must be completed with several points in mind. First, the graphic analysis above treats problems of resource allocation and institutional alternatives from the standpoint of static economic theory. Weather uncertainty adds a degree of complexity to the analysis, making the actual situation dynamic rather than static. That is, the marginal value product curve for the water resource has an expected value and variance. Irrigators attempting to optimally allocate the resource act upon the expected value, but, they do not know whether the allocation is optimal unitl the growing season is complete. A dynamic MVP curve complicates specification of the optimal allocation of water under the various water-use regulatory alternatives. No further attempt is made to incorporate dynamics into the conceptual issues, but the dynamics are considered in the quantitative analysis of the three alternatives presented later in this bulletin.

Second the institutional alternatives considered by no means exhaust the possibilities. Additional restraints might include (1) a lump sum tax or well tax on each irrigation well; (2) a limit on the number of wells per section or per farm; (3) a limit on well spacing, etc. The possibility of importing water to sustain irrigated acreage could also be evaluated. Time and resources did not permit evaluation of additional alternatives.

Third, maximization of long-run social benefits from the use of water was previously cited as the dominant goal of water resource use. From society's standpoint, water is optimally allocated when individual irrigators consider marginal social costs rather than marginal private costs in allocating water resources. The water-use regulatory alternatives suggested herein are admittedly not designed to force irrigators to consider the full marginal social costs of water use. However, they do provide policy makers with viable alternatives to unrestricted water use while inducing irrigators to narrow the divergence between private and social costs.

The Simulation Model

A firm-level simulation model is used as the basic model in the analysis of the three alternative means of water-use regulation. The

General Agricultural Firm Simulator developed by Hutton and Hinman [51] is modified to simulate a representative farm for the study area. The major modification made to the General Agricultural Firm Simulator in this study is the development of a new production subset. The Production Subset is designed to overcome some of the shortcomings of the General Agricultural Firm Simulator while adding a dimension of sophistication and realism to the production process not previously obtained in simulation models designed to solve economic problems. Some of the general characteristics of the General Agricultural Firm Simulator are discussed below followed by a detailed discussion of the development and structure of the Production Subset used in the study.

The Firm Model

The General Agricultural Firm Simulator, a computer simulation routine useful to solve a variety of farm firm simulation models, consists of a master program and a series of subroutines. The model is designed to utilize information on the production, financial and institutional resources available to the firm, as well as crop production, livestock production and marketing alternatives. The precise nature of organizing the data, the logic of the operation of the General Agricultural Firm Simulator and the printout of the Simulator results are discussed elsewhere [61, pp. 43-48].

A Production Subset was developed to simulate yields and irrigation water use in a framework that considers variable rainfall, evapotranspiration and the effects of soil moisture stress during critical stages of plant development on final crop yield. This method of computing yields for both irrigated and dryland crops replaces the assumption of normally and independently distributed yields in the General Agricultural Firm Simulator. It also replaces the assumption of fixed irrigation requirements by season with requirements that depend on the weather conditions over the production year.

The Production Subset

Building on earlier soil moisture-crop yield models [3, 4, 30, 31, 32, 33, 68, 98, 107] a multiple-crop simulation model was developed for the major dryland and irrigated crops in the study area. This model is presented in detail in another publication [62]. Only a brief summary is included here. The basic idea embodied in the production subset is that crop yields can be estimated as a function of soil and atmospheric conditions, or soil moisture stress and atmospheric stress, during critical stages of plant development. If soil moisture and atmospheric conditions are ideal throughout the growing season, some potential yield is achieved for each crop.

When sufficient water is not maintained in the plant root system, soil moisture stress occurs and the result is a reduction in crop yield. The amount of yield reduction depends upon the length and severity of moisture and atmospheric stress in relation to the stage of plant development. Even when soil moisture is adequate, severe atmospheric conditions can cause plant stress and reductions in crop yield. A combination of high temperature, low relative humidity and high wind movement creates a demand for more moisture than the plant is able to transpire. The resulting plant stress causes a reduction in final crop yield. Thus, yield reduction for a crop is a function of the length and severity of moisture and atmospheric stress as they relate to the critical stages of plant development.

The crop yield reduction relationship, which assumes the combined affects of soil water and atmospheric stress to be additive, may be stated in equation form as

$$(1)\ YR_{ij}^{k} = \theta_{j}^{k} SWD_{ij} + b_{j}^{k}(P_{ij} - P_{a})$$

where YR_{ij}^{k} is yield reduction, day i, stage j, crop k; θ_{j}^{k} is yield reduction, in units per day, resulting from adverse soil water conditions, stage j, crop k; SWD_{ij} represents the proportion of soil water available for plant use, day i, stage j; b_{j}^{k} is yield reduction in units per day due to severe atmospheric demands upon the plant, stage j, crop k; P_{ij} is pan evaporation in inches, day i, stage j; and P_{a} is a critical pan evaporation level at or below which no yield reductions occur that are directly attributable to severe atmospheric conditions.

To compute daily yield reductions, the production subset requires daily estimates of soil water and atmospheric stress. A soil water balance was constructed to provide daily soil water levels adjusted to reflect additions due to rainfall and irrigation applications and subtractions due to evapotranspiration. Daily rainfall events were generated from discrete empirical probability distributions for each of 14 two-week periods throughout the growing season. Daily pan evaporation values were generated from 14 lognormal distributions of pan evaporation. The soil water balance utilized the rainfall and pan evaporation values, irrigation applications, and assumptions regarding field capacity and permanent wilting point for the soil profile, water movement within the profile, and stages of plant development to compute the level of soil water available for each crop each day throughout the growing season.

The coefficients θ_j and b_j in equation (1) were estimated for three critical stages of development for grain sorghum, four critical stages for wheat, and five critical stages for corn. Total yield reduction was obtained by summing i daily yield reductions for each of j stages of plant development for each crop. Final yield was then computed by subtracting total yield reduction caused by soil water and atmospheric stress conditions from the potential yield that would be expected if adequate moisture conditions existed throughout the entire growing season.

The production subset was completed by combining the soil-water balance and crop-yield equations. The resulting crop yields and irrigation water use were a portion of the input data for the General Agricultural Firm Simulator.[3]

Representative Firm Situations

Defining Typical Resource Situations

The primary basis for selecting typical resource situations is the saturated thickness of the Ogallala Formation. Saturated thickness is a critical determinant of both the quantity of water in storage and the yield of an irrigation well or system in gallons per minute. The land area and amount of water in storage is summarized by

3. Considerable time and effort was devoted to model development and verification. Series of dryland and irrigated yields were generated under alternative rainfall and irrigation patterns, and these yield series were judged realistic by agronomists, agricultural engineers, irrigation specialists and farm management experts. A complete discussion of model development and verification is presented in [62].

Table 2. Water Resources Inventory of Study Area, 1965

Initial Saturated Thickness	Item	Depth to Water (Pump Lift)								
		<50'	51'-100'	101'-150'	151'-200'	201'-250'	251'-300'	301'-350'	>350'	Total
0'-100'	No. of Acres	489,855	819,867	459,018	537,788	151,708	100,507	49,239	37,432	2,645,414
	% of Total	4.39	7.35	4.12	4.82	1.36	0.90	0.44	0.35	23.73
	Ac. Ft. in Storage	3,673,912	6,150,352	3,442,635	4,033,411	1,137,810	753,803	369,291	280,740	19,841,954
	% of Total	.99	1.66	0.94	1.09	0.31	0.20	0.10	0.08	5.37
101'-200'	No. of Acres	310,964	537,159	359,570	607,113	358,379	255,319	94,347	25,703	2,548,554
	% of Total	2.79	4.82	3.22	5.45	3.21	2.29	0.85	0.23	22.86
	Ac. Ft. in Storage	6,996,690	12,086,079	8,090,324	13,660,044	8,063,527	5,744,678	2,122,807	578,318	57,342,467
	% of Total	1.89	3.27	2.19	3.70	2.18	1.55	0.57	0.16	15.51
201'-300'	No. of Acres	215,693	632,714	423,583	799,750	329,340	214,759	210,520	42,843	2,869,472
	% of Total	1.94	5.68	3.80	7.17	2.95	1.93	1.89	0.38	25.74
	Ac. Ft. in Storage	8,088,488	23,726,776	17,599,724	28,954,987	12,350,250	8,053,463	7,894,500	1,606,612	108,274,800
	% of Total	2.19	6.42	4.76	7.83	3.34	2.18	2.14	0.43	29.29
301'-400'	No. of Acres	145,662	338,786	368,044	879,331	133,014	35,880	51,460	13,277	1,965,454
	% of Total	1.31	3.04	3.30	7.89	1.19	0.32	0.46	0.12	17.63
	Ac. Ft. in Storage	7,647,255	17,786,266	18,622,760	46,165,088	6,983,235	1,883,700	2,701,650	697,042	102,486,996
	% of Total	2.07	4.81	5.04	12.49	1.88	0.51	0.73	0.19	27.72
401'-500'	No. of Acres	30,012	117,486	298,929	203,433	18,475	18,385	20,069	7,814	714,603
	% of Total	0.27	1.05	2.68	1.82	0.17	0.17	0.18	0.07	6.41
	Ac. Ft. in Storage	2,025,810	7,930,305	20,177,708	13,731,727	1,247,063	1,240,988	1,354,658	527,445	48,235,704
	% of Total	0.55	2.14	5.46	3.71	0.34	0.34	0.37	0.14	13.05
>500'	No. of Acres	32,890	79,348	216,646	70,708	1,410	1,070	3,769	—	405,841
	% of Total	0.30	0.71	1.94	0.63	0.01	0.01	.03	—	3.63
	Ac. Ft. in Storage	2,713,425	6,546,210	17,873,295	5,833,410	116,325	88,275	310,943	—	33,481,883
	% of Total	0.73	1.77	4.84	1.58	0.03	0.02	0.08	—	9.06
Total	No. of Acres	1,225,076	2,525,360	2,126,060	3,098,123	992,326	625,920	429,404	127,069	11,149,338
	% of Total	11.00	22.65	19.06	27.78	8.89	5.62	3.85	1.15	100.00
	Ac. Ft. in Storage	31,145,580	74,225,988	85,806,446	112,378,667	29,898,210	17,764,907	14,753,849	3,690,157	369,663,804
	% of Total	8.42	20.08	23.22	[illegible]	8.09	4.80	3.99	1.0[illegible]	100.00

saturated thickness interval in Table 2. The number of acres overlying each saturated thickness interval and the percent of the total study area represented by each saturated thickness interval are presented.

Although the range in saturated thickness in Table 2 suggests it would be desirable to define several resource situations for analysis, the available resources limited the analysis to two basic resource situations, designed to represent "poor" and "adequate" water conditions for this study. The saturated thickness intervals 100 and 101-200 feet are combined to represent the poor water situation. The remaining four saturated thickness intervals are combined to represent the adequate water situation. The two basic resource situations are defined in Table 3.

Table 3. Definition of Two Basic Resource Situations for the Study Area

Resource Situation	Weighted Ave. Feet of Sat. Thickness	Acres Within Each Resource Situation	Percent of Study Area Acres	Acre Feet of Water Within Each Resource Situation	Percent of Study Area Water
1	100	5,193,968	46.59	77,184,421	20.88
2	325	5,955,370	53.41	292,479,383	79.12

Resource Situation 1 represents 46.59 percent of the total land area, however, the underlying formation contains only 20.88 percent of the available water. Resource Situation 2 represents 53.41 percent of the surface area, however, overlies 79.12 percent of the available water. The weighted average saturated thickness of the underground formation for Resource Situation 2 is approximately 325 feet. Each resource situation is characterized by a representative farm firm and the effects of continued pumping on saturated thickness and well yield are simulated through time.

Over time, the incidence and distribution of benefits and costs of irrigating from the Central Ogallala Formation will not be uniform. Irrigation wells in Resource Situation 1 will yield 780 g.p.m. when pumped from 100 feet of saturated thickness of Ogallala Formation, assuming average permeability. As saturated thickness declines, well yields decline and irrigators are forced to drill additional irrigation wells to maintain their historic production pattern. The irrigator eventually is forced to reduce irrigated acreage and return to dryland farming. The return to dryland farming comes not as a result of physical exhaustion of the aquifer, but as a direct result of rapidly rising irrigation costs.

Irrigation operators pumping with 325 feet of saturated thickness do not experience the immediate decline in well yields and rising pumping costs of irrigators in Resource Situation 1. Properly designed irrigation wells yield 1,000 g.p.m. until the saturated thickness declines from 325 feet to approximately 125 feet. Assuming an average rate of decline of five feet or less per year, suggests irrigators in Resource Situation 2 will experience 40 or more years of adequate water before well yields decline appreciably and pumping costs rise rapidly.

A Representative Farm for the Study Area

Time, human resources and computer problems act as significant constraints when defining a manageable number of representative farms or resource situations to be programmed. Given the three institutional alternatives with respect to water use and the two basic resource situations defined above, only one modal representative irrigated farm operation was defined for the study area. This modal operation was synthesized from individual farm surveys taken from a random sample of 78 irrigation operators in the study area during the summer of 1970.

The distribution of farm sizes for the 78 operations reveals that the modal farm size is between 500 and 1,000 acres and that the farm sizes representing the greatest number of farms tend to be associated with intervals containing multiples of 640 acres—full sections. Closer examination reveals that the largest number of farms range in size from 601 to 700 acres. Since farms have a tendancy to be even sections in size, a modal representative farm of 640 acres, or one section, is defined for this study.

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4. The random sample of 78 irrigated operators was a portion of a more extensive survey in 1970 taken by Wyatte L. Harman and Roy E. Hatch, Agricultural Economists, Farm Production Economics Division, Economic Research Service, U.S. Department of Agriculture, in connection with a study for essentially the same study area.

Organization of Production for the Representative Farm

No effort was made to determine an optimum production organization for the representative farm. An organization representing what farmers produce was used to more accurately represent the effect of the institutional alternative on farms in the area. Surveys from the 78 randomly sampled farm operations were utilized to develop an organization for the representative farm. The organization of production is presented in Table 4. A total of 315 acres of cropland are irrigated. Grain sorghum and corn comprise 230 acres of irrigated summer crops and the remaining 85 acres are planted in winter wheat. There are 30 acres of dryland grain sorghum and 85 acres of dryland wheat.

Each of the above crops is divided into one or more crop blocks (fields) and an average yield per acre computed for each block by the production subset. For example, each dryland crop is planted in a single crop block. Irrigated wheat and corn are each planted in two crop blocks. Irrigated grain sorghum is planted in four crop blocks. The acreage in each block appears in parentheses in Table 4. Each crop block has its own soil moisture balance to maintain a daily record of stress conditions. The farm operator is assumed to irrigate each crop block by block. Thus, if pumping capacity is insufficient to irrigate an entire crop, perhaps only one block suffers severe moisture stress rather than the entire crop suffering moderate stress.

All grain sorghum is assumed harvested for grain. Two-thirds of the corn is harvested for grain and one-third for silage. The remaining 165 acres of cropland is divided among three land use categories—66 acres are idle or fallow, 84 acres are planted to dryland small grain graze out and 15 acres are assumed lost due to turnrows, etc. The representative farm also contains 40 acres of native pasture. The homestead, buildings and roads are assumed to occupy the remaining five acres. Assumptions concerning the machinery complement, overhead costs and labor requirements are considered representative of the study area. The listing of the machinery complement is given by Mapp [61, pp. 260-261]. Annual overhead costs for the 640-acre cash grain farm total $3,380 [61, p. 93]. Family labor is assumed available at the rate of 200 hours per month and additional labor may be hired in eight-hour increments at $2.00 per hour.

Table 4. The Organization for the Representative Cash Grain Farm, Central Ogallala Formation

Cropland	(Acres)
Irrigated Grain Sorghum	170
Block G1 (80)	
Block G2 (40)	
Block G3 (30)	
Block G4 (20)	
Irrigated Wheat	85
Block W1 (65)	
Block W2 (20)	
Irrigated Corn	60
Block C1 (40)	
Block C2 (20)	
Dryland Grain Sorghum	30
Block G5 (30)	
Dryland Wheat	85
Block W3 (85)	
Idle or Fallow	66
Small Grain Graze Out	84
Lost to Turnrows	15
Total Cropland	595
Pastureland	
Dryland Non-Tillable Pasture	40
Total Pastureland	40
Other Land	
Home, Buildings and Roads	5
Total Other Land	5
Total Land in Farm	640
Allotments	
Wheat	185
Feed Grain	120

Price Assumptions

Prices used in this analysis are "adjusted normalized prices" issued by the Water Resources Council [52]. The price estimates are considered "normalized" since the use of long-term, nonlinear trend lines removes many of the abnormalities caused by weather and other short-term chance events. The normalized prices are then adjusted to reduce the influence of Government price support programs. Adjusted normalized prices for commodities are further adjusted to the State level through the use of a ratio of State to U.S. normalized prices received by farmers.

U.S. adjusted normalized prices are $1.30 per bushel for wheat, $0.95 per bushel for grain sorghum and $1.05 per bushel for corn. The average ratio of State to U.S. prices for the study area is 0.995, 0.985 and 1.06 for wheat, grain sorghum and corn, respectively. The adjusted normalized prices computed for use in this study were $1.20 per bushel for wheat, $0.94 per bushel for grain sorghum and $1.11 per bushel for corn. These prices were further adjusted to reflect the value per bushel of wheat and feed grain certificates in effect at the time of the study. After adjustments fro the value per bushel of certificate payments, priced were $1.96 per bushel for wheat, $1.18 per bushel for corn and $1.01 per bushel for grain sorghum.

Input prices used at the time of the study included the following: $2.25 per bushel for wheat seed, $.07 per pound for nitrogen, $2.00 per hour for hired labor, seven percent interest on annual capital, and harvesting and hauling costs of $3.50 per acre and $.08 per bushel, respectively, for wheat.

Irrigation Wells and Pumping Costs

Representative farm firms for both Resource Situations 1 and 2 are assumed to have one irrigation well at the beginning of all simulation runs.[5] The adequate-water farm firms (Resource Situation 2) are assumed to have an irrigation well capable of producing 1,000 g.p.m. over the 20-year span of each simulation run. However, firms in Resource Situation 1, with 100 feet of saturated thickness, are assumed to begin each 20-year run with a single irrigation well, pump, motor and distribution system, capable of pumping 780 g.p.m. during the initial year of the simulation run. With the pump bowls located as near the redbed underlying the Ogallala Formation as practical, each year's pumping has several effects. First, the saturated thickness of the formation is reduced. Second, the reduction in saturated thickness

5. See Mapp [61, pp. 96-100] for a discussion of the method used to compute the initial well yields for each resource situation and the amount of saturated thickness required to sustain a 1,000 g.p.m. yield.

leads to a reduction in pump yield. Third, the reduced capacity increases the per unit cost of delivering each acre inch of water to the plants. Fourth, the reduced capacity also alters the operator's irrigation schedule by making it more difficult to achieve timely water applications.

The relationship between declining saturated thickness and reduced well capacity is expressed in equation (2).[6]

$$(2)\quad Q_t = \left(\frac{H_t}{H_{t-1}}\right)^2 Q_{t-1}$$

where Q_t represents the well capacity in the current period t; Q_{t-1} represents the well capacity in the preceding period t-1; H_t represents the remaining feet of saturated thickness in the current period t; and H_{t-1} represents the feet of saturated thickness in the preceding period t-1.

Equation (2) is used to compute current pumping capacity at the beginning of each crop year within the Production Subset of the model. Experimentation with the model reveals that at least 700-g.p.m. well capacity is required to adequately irrigate the original production organization on the representative farm. Thus, a decision rule is built into the Production Subset which allows the irrigator to drill an additional well if pumping capacity falls below 750 g.p.m. during a crop year. The new well is assumed drilled during the non-irrigation season and pumping capacity the following year is increased by the capacity of the existing well. For example, if the yield of irrigation well declines below 750 g.p.m. during the current season to, say, 700 g.p.m. by the end of the crop year, the producer is assumed to drill a second well and connect it to the original distribution system which increases the system capacity to 1,400 g.p.m. for the following crop year. Yields for both wells then decline as the saturated thickness diminishes until system capacity falls below 750 g.p.m. again. Then the irrigator is assumed to drill a third well, designed to deliver the average yield of the other two wells, raising system pumping capacity by 50 percent. Three irrigation wells is the maximum assumed for the one-section representative farm firm.

Detailed information regarding investment, ownership and pumping costs for irrigation wells of Resource Situations 1 and 2 are presented in [61, pp. 318-324]. All irrigation systems utilized in

6. Equation (2) was developed in the Southern High Plains of Texas for irrigation wells pumping from the Ogallala Formation. The relation was obtained by correspondence with Mr. Frank A. Rayner, Manager of the High Plains Underground Water Conservation District, Lubbock, Texas, and Mr. Frank Hughes, ERS, USDA, Texas A & M University, College Station, Texas.

the model are furrow or surface systems suited to Richfield clay loam soils.

Development of Irrigation Strategies

It is not difficult to prescribe an optimum irrigation strategy for the farm operator under static conditions. Static economic theory indicates the rational operator should utilize each unit of irrigation water in its highest value use so that the marginal value product of the last unit applied just equals its marginal resource cost.

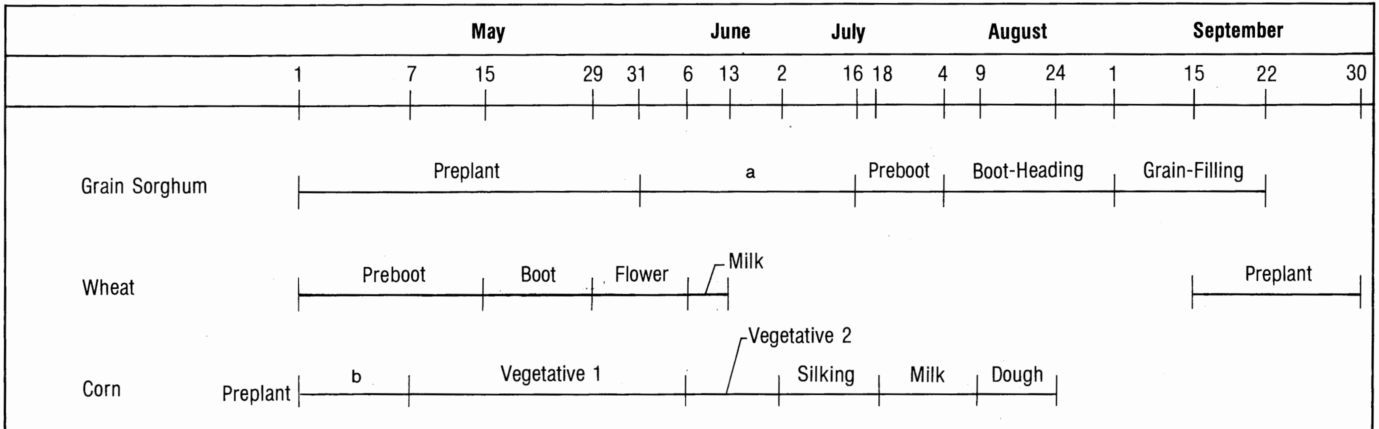
The optimal strategy prescribed under static conditions is difficult to apply under the dynamic conditions faced by the irrigator in the field. Static theory implies the ability to change water applications instantaneously from one crop to another. In practice, once the operator begins to irrigate, he finds it economical to add from 1.0 to 3.0 inches of water to the soil profile of a crop before changing the irrigation set to another crop or another field. Thus, even though water is the type of resource that appears to be infinitely divisible, problems of indivisibilities exist. However, these indivisibilities do not invalidate the economic concept of applying water to its highest valued use. Each irrigation operator has an idea of the critical water-use periods for each crop and which of the several crops requiring water during a specific period has the highest use value for the irrigation water available. He applies water during a specific period first to the crop which has the highest use value (marginal value product) for that unit of irrigation water. Once that crop has received an irrigation application, the crop or crop block having the highest marginal value product for the next unit of irrigation water receives the next irrigation application. The operator may switch crop priorities from one part of the growing season to another in response to changes in the value of irrigation water among crops.

Delineation of Irrigation Periods

This line of reasoning leads to the development of a series of irrigation strategies for the growing season. Table 5 presents a crop calendar covering the period May 1 through September 30. The crop calendar shows the critical stages of plant development for grain sorghum, wheat and corn and indicates the periods when two or more crops are in direct competition for irrigation water.

The entire period covered by the crop calendar is divided into five

Table 5. Delineation of Critical Stages of Plant Development, Irrigation Priorities and Irrigation Strategies



Critical Periods	(1) May 1-May 15	(2) May 16-June 5	(3) June 6-August 4	(4) August 5-September 15	(5) Sept. 16-30
Irrigation Priorities[c]	G,W,C	W,C,G	C,G	G,C	G,W
Pumping Days	14	20	56	39	14

[a]No stage name is given to grain sorghum between preplant irrigation applications and preboot stage. Moisture stress during this period has little effect if moisture is adequate during subsequent stages of development.

[b]Plant emergence occurs between May 1 and May 7.

[c]Irrigation priorities G, W and C represent grain sorghum, wheat and corn, respectively. All blocks of the crop listed first in a critical period are irrigated before any block of the second or third priority crops.

irrigation periods. The basis for selection the beginning point of each period is the beginning of a critical stage of plant development for a crop. For instance, irrigation period 2 begins on May 16, when wheat reaches boot stage, and lasts until June 6 when the late vegetative stage for corn begins. Irrigation priorities established during this period are wheat first, corn second and grain sorghum last. These priorities are based on the marginal value product of irrigation water on the crops during this 20-day period of the growing season. The information presented in Table 5 for periods 2, 3, 4 and 5 can be interpreted in a similar manner.

Irrigation Strategies by Periods

Application of irrigation water depends upon the level of soil moisture existing in the soil profile of a crop. The model assumes that the decision to irrigate is made when the level of soil moisture falls below 50 percent of available soil moisture, or 12.5 inches. If soil moisture in the entire profile for a crop equals or exceeds 12.5 inches, no irrigation water is applied. If available soil moisture falls below the 50 percent available level during a critical stage of development, additional water is applied based on the priorities discussed above and available pumping capacity. If sufficient water is available, the entire crop receives a 3.0-inch addition to the soil profile. However, if plants on the part of the field already irrigated begin to show signs of plant stress before the entire application can be completed, irrigators are assumed to reduce the application rate on the remaining acres, and return to the original portion of the crop to begin a new application. These assumptions appear reasonable based on the actions of irrigators in the area.

Varying irrigation rates on shifting numbers of acres during different stages of plant development is extremely difficult to handle from a modeling standpoint. Therefore, as indicated in Table 4, total acreage of each irrigated crop is divided into several blocks. The 170.0 acres of irrigated grain sorghum are divided into four blocks of 80.0 acres, 40.0 acres, 30.0 acres and 20.0 acres. Similarly, the irrigated wheat and the irrigated corn are each divided into two blocks. Block 1 of any crop is always irrigated first, followed by block 2, etc. If, using grain sorghum as an example, block 4 is being irrigated and block 1 begins to suffer moisture stress, the irrigation application rate is reduced on block 4 and block 1 is the next block to be irrigated.

The general procedure for scheduling and executing irrigation applications is the same for every period and may be discussed in general terms. Each period has a set of crop irrigation priorities as outlined in Table 6. The priorities determine the order in which soil moisture values are checked against the critical value (usually 50 percent available soil moisture or 12.5 inches). Assume the order of priorities is (1) grain sorghum, (2) wheat and (3) corn, as it is for period 1. On the first day of the period, soil moisture for the first block of grain sorghum, G1, is checked against 12.5 inches of soil moisture. If soil moisture for G1 equals or exceeds 12.5 inches, no irrigation application is scheduled for G1 and soil moisture for G2 is checked against 12.5 inches, etc. If all four grain sorghum blocks have soil moisture in excess of 12.5 inches, then soil moisture for the first block of wheat (W1), the second priority crop, is checked against 10.98 inches.

After soil moisture for both blocks of the third priority crop, corn, have been checked against 10.98 inches, and soil moisture for all blocks is found to exceed their critical value, the day is incremented to day 2 of the period and soil moisture under the first block of the first priority crop is again checked against 12.5 inches. In the above example, no irrigation application would be scheduled during day 1 of period 1.

Now consider the usual situation where an irrigation application is required. Assume that on day 1 of the period, soil moisture under G1 is less than 12.5 inches. The farm operator schedules an irrigation application for G1. Ideally, once an application has begun, he would like to add 3.0 inches of soil moisture to the G1 profile. Due to evapotransporation and water losses from leakage and seepage, only about two-thirds of the water pumped from the aquifer enters the soil profile of the irrigated crop. Therefore, 4.5 inches must be drawn from the aquifer to insure a 3.0-inch addition to the soil profile. Based on the requirement of 4.5 acre inches per acre, the irrigation water requirement is computed from (3):

$$(3)\quad WR_{ij} = 4.5\ AC_{ij}$$

where Wr_{ij} equals the water requirement, block i, crop j; and AC_{ij} equals the acres planted in block 1, crop j.

Then the water requirement is compared with the pumping capacity for the period. Pumping capacity is computed based on gallons per minute delivered by the irrigation system as follows:

$$(4)\quad BPC_i = (GPM \times 1440.0 \times DAYS_i)/27{,}155.0$$

where BPC_i equals the beginning pumping capacity for period i in acre inches; GPM equals the irrigation system pumping capacity in

Table 6. Moisture Levels at Which Irrigations are Scheduled and Priorities Established by Irrigation Periods

	Irrigation Period											
	1			2			3		4		5	
Irrigation Priority Order	GS	W	C	W	C	GS	C	GS	GS	C	GS	W
Inches of Soil Moisture at which Irrigations are Scheduled	12.50	10.98	10.98	12.50	12.50	12.50	12.50	10.98	12.50	12.50	10.98	12.50
Inches of Soil Moisture at which Priority on Water is Established	9.45	10.98	10.98	10.98	10.98	10.98	10.98	9.45	10.98	10.98	9.45	9.45

gallons per minute: 1440.0 equals the number of minutes per day; $DAYS_i$ equals the number of days in period i; and 27,155.0 equals the gallons per acre inch.

Assuming that pumping capacity for the period equals or exceeds the water requirement for G1, the irrigation application is initiated. The number of days required to apply WR_{ij} acre inches is computed and no other crops can be irrigated until the application of G1 has been completed. The total application is divided by the number of days required to apply it, and the appropriate proportion is added to soil moisture each day. Once the application on G1 is complete, the remaining pumping capacity for the period is computed and soil moisture under the second block of the top priority crop, G2, is checked against 12.5 inches. If soil moisture exceeds 12.5 inches, soil moisture under G3 is checked, etc. If, however, G2 soil moisture is less than 12.5 inches, its water requirement is computed using (3) and is then compared to the remaining pumping capacity for the period. If sufficient capacity exists, the irrigation is scheduled, the number of days required computed and the appropriate amount of moisture per day added to the soil profile.

No other crop may be irrigated until the application on G2 has been completed. The G2 water requirement is deducted from pumping capacity for the period, and then soil moisture for G3 is checked against 12.5 inches. This procedure continues unaltered until one of four following events occurs. (a) The water requirement for any block of a crop exceeds the remaining pumping capacity for the period. (b) The number of days remaining in the period is insufficient to allow a full irrigation. (c) A block of higher priority reaches a low soil moisture level while a low priority crop is being irrigated. (d) The period comes to an end. These events are considered in turn below.

If the water requirement for a block of a crop exceeds the remaining pumping capacity for the period, based on a 4.5-inch application per acre, the number of acre inches which can be applied per acre is computed. If that number equals or exceeds 1.5 acre inches per acre, the irrigation is scheduled and the application made. If at least 1.5 acre inches per acre cannot be applied, no irrigation application is made to the block in question.

If the number of days remaining in the period is insufficient to allow a full irrigation, water is applied at the computed rate per day until the period ends.

If a block of higher priority reaches a low soil moisture level while a lower priority crop or block is being scheduled for irrigation, the irrigation application on that block is reduced to 1.5 acre inches per acre. Then the higher priority crop moisture is checked, and a full 4.5-inch irrigation application is made, assuming time and pumping capacity exist to complete the application.

When the period comes to an end, no further irrigations are scheduled based on crop priorities for the current period. Soil moisture under block 1 of the highest priority crop in the next period is checked against 12.5 inches of soil moisture.

The same procedure continues through all five of the irrigation periods. At the end of the crop year, crop yields on each block of each crop are computed based on soil moisture and atmospheric stress suffered during the critical stages of development and accumulated throughout the growing season.

The general strategy to allocate irrigation water within years described above is applied to the representative farm under each of the three methods of regulating water use. The modifications made to apply this strategy under the three sets of institutional restraints are discussed below.

No Institutional Restraints on Water Use

For the unrestricted water-use alternative, the decision rules followed by irrigators are based upon the level of available soil moisture during critical stages of plant development as outlined in previous sections. Irrigators in Resource Situation 1 face declining well yields over the 20-year simulated time period. When capacity of the irrigation system falls below 750 g.p.m. in a given year, the irrigator is assumed to drill a new well at the end of that year. When the operator has three irrigation wells, his response to declining well yields and rising pumping costs is to reduce the number of irrigated acres. The decision rule used to reduce irrigated acres is based on a comparison of net returns per acre above variable costs for each irrigated block and opportunity cost net returns per acre for the best dryland alternative — dryland wheat. Opportunity cost net returns on dryland wheat, considered as returns to land, overhead, risk and management, are $5.24 per acre [12, p. 115]. Every year after the third well has been added the net return per acre above variable costs in each block is compared to the $5.24, the opportunity cost for dryland wheat. If the opportunity cost dryland net return is greater, the block is planted to dryland wheat the following year.

A Quantity Limit on Water Use

The second institutional alternative restricts the quantity of irrigation water the individual operator is allowed to pump during the crop year to 1.5 acre feet of irrigation water per acre of water rights per crop year. Assuming the representative farm firms for this study have water rights to irrigate 315 acres limits the irrigator to pumping 472.5 acre feet (or 5,670 acre inches) per year.

The controlling agency is assumed to say nothing about the allocation or distribution of this water among periods of the crop year. The irrigator is free to pump his system at capacity from the beginning of the irrigation season until he has arrived at the quantity limit, or limit pumping in the early periods due to uncertainty about future moisture conditions. The rational irrigator is assumed to hedge current pumping due to uncertainty about future water needs during later stages of plant development. He is assumed to pump acording to soil moisture depletion levels and crop priorities established for the unconstrained simulation runs discussed previously, however, establishes maximum amounts of water to be added to each crop during each stage of plant development. The maximum levels by crops and irrigation periods are reflected in Table 7.

These figures indicate, for example, that no more than 4.5 acre inches of irrigation water will be applied to each acre of grain sorghum during irrigation period 1. With an irrigation efficiency of two-thirds, a 3.0-inch real addition to the soil profile is implied by a

Table 7. Maximum Inches of Water Applied Per Acre by Crops and Periods of the Growing Season in Response to a Quantity Limitation

Period	Grain Sorghum	Wheat	Corn
April	0.0	0.0	6.0
Period 1	4.5	4.5	0.0
Period 2	4.5	9.0	4.5
Period 3	9.0	0.0	18.0
Period 4	13.5	0.0	4.5
Period 5	0.0	9.0	0.0
Total	31.5	22.5	33.0

4.5 acre inch per acre water application. These self-imposed irrigation guidelines provide enough flexibility to allow sufficient water to be applied during very dry years, yet induce the irrigator to conserve water for subsequent periods to meet unexpected demands. During a year of high and timely rainfall, the irrigator will likely not pump 5,670 acre inches of water. However, during a year characterized by either untimely or low rainfall, the irrigator may easily reach the quantity limit during irrigation period 4 and be unable to complete grain sorghum irrigations or to prewater wheat during September.

No change in production organization is assumed. It might be argued that the rational irrigator would respond to a quantity limitation by reducing irrigated acres to the maximum number he can fully irrigate. While this course of action makes sense from an economic standpoint, it is not being followed by the operators experiencing declining well yields and water supplies. The tendency is to protect the historic production organization by applying less water per acre while maintaining the same number of acres [12, p. 119]. Once it becomes unprofitable to irrigate a crop block, however, producers naturally respond by reducing irrigated acreage. The net returns per acre above total variable costs for each crop block is compared with dryland wheat opportunity cost net returns per acre. Crop blocks whose net returns per acre fail to exceed opportunity cost net returns per acre are converted to dryland wheat the following year in a multi-period run.

Graduated Tax on Water Pumped Above the Quantity Limitation

The third institutional alternative considered assumes that the irrigator is permitted to pump in excess of 5,670 acre inches per year if he is willing to pay a tax on each acre inch of water pumped above the quantity limitation. A tax rate of $.50 per acre inch ($6.00 per acre foot) is assumed. The model assumes decision rules for simulation of the quantity limitation, specified in the previous section, are followed until the quantity limitation is reached. Thereafter, the irrigator is assumed to decide whether or not to irrigate based upon the potential loss in yield which will occur if the irrigation is not applied.

The critical decisions involve whether or not to continue irrigating grain sorghum during irrigation period 4 and whether or not to apply a preplant irrigation on wheat during irrigation period 5. The preplant irrigation on wheat is quite often of critical importance if a good stand is to be achieved. In the Production Subset of the model, failure to preplant irrigated wheat is assumed to reduce the potential yield by 15 bushels. Fifteen bushels of wheat at $1.29 per bushel returns gross revenue of $19.35. The variable cost of the additional irrigation is approximately $8.70.[7] The value of the marginal product resulting from an additional irrigation on wheat clearly exceeds the marginal resource cost. Thus, the irrigator is assumed to apply a preplant irrigation on wheat during irrigation period 5 every year.

The decision whether or not to irrigate grain sorghum during irrigation period 4 is a function of soil moisture and days of potential yield reduction remaining in irrigation period 4. If soil moisture is low enough that the potential yield reduction is equal to or greater than ten bushels, the decision is to irrigate.[8] All wells are metered and the irrigator pays a tax of $0.50 per acre inch on each acre inch in excess of the 5,670 acre inches pumped during the crop year.

Results of Simulating Alternative Methods of Water-Use Regulation

This section summarizes and compares the effects of unrestricted pumping, a quantity limitation and a graduated tax on water pumped above the quantity limitation on representative firms for two water resource situations. Operation of the representative firms was simulated under each method of regulation over a 20-year time horizon and each method of regulation was replicated 15 times. Results of the analysis presented in detail in the appendix, are summarized below.

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7. Variable costs of $8.70 include variable pumping costs of $1.00 per acre inch for a 4.5-inch application, additional labor costs of $0.75, added harvesting and hauling costs of $1.20 and water taxes of $2.25.

8. Gross revenues from nine and ten bushels of grain sorghum at $0.94 per bushel are $8.46 and $9.40, respectively. The cost of the additional irrigation, assuming variable pumping cost per acre inch is $1.00, additional labor cost is $0.75, tax payments are $2.25 and added harvesting and hauling costs are either $0.99 or $1.10, total $8.49 and $8.60 for nine and ten bushels potential yield reduction, respectively. The added costs exceed added revenues for a nine-bushel potential yield reduction, however, added revenues exceed added costs and an additional irrigation is justified if potential yield reduction is equal to or greater than ten bushels.

Statistical Comparisons of Unrestricted Pumping, a Quantity Limitation and a Graduated Tax on Resource Situation 1

Resource Situation 1 represents the poor water situation for the study area. The effect each method of water-use regulation has on water use, remaining saturated thickness, net farm income, income variability (as measured by the coefficient of variation) and net worth at the end of the 20-year simulation period for resource situation 1 is discussed in this section. Tests are conducted to determine whether mean values of the relevant variables over the 20-year period differ significantly. Implications are drawn regarding differences in results of the three alternatives and their effects on the firm and the region.

Acre Inches Pumped

Figure 6 illustrates the effect of each water-use alternative on mean acres inches pumped through time. From year 1 through year 10, mean values of total acre inches pumped under unrestricted pumping exceed acre inches pumped under the quantity limitation

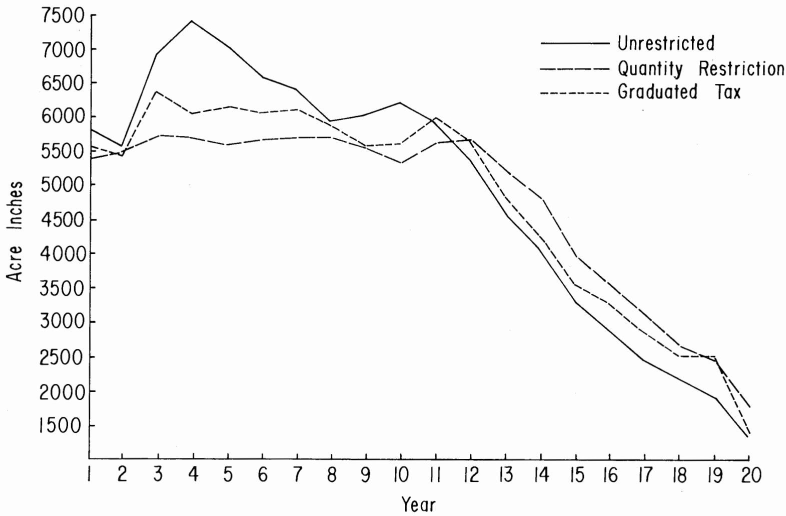

Figure 6. A Comparison of Mean Acre Inches of Irrigation Water Pumped Under Alternative Water-Use Regulation Methods for Resource Situation 1

and graduated tax alternatives. During the same period, the irrigator paying a graduated tax for each acre inch above the quantity limit finds it profitable to pump water in excess of the quantity limitation every year except one. This exception occurred during year 2 when pumping capacity is limited. Irrigation well 3 is usually added by year 10 under the unrestricted alternative; by year 11 under the graduated tax alternative; and by year 12 under the quantity limitation. The lag which develops reflects the different rates of pumping under each alternative in early years of the simulated time period. High early period pumping rates under the unrestricted alternative lead to lower system capacities and earlier additions of well 3. Lower pumping rates under the quantity limitation result in a slower decline in system pumping capacity and thus a lag in the requirement for well 3 until about year 12.

From year 12 to year 20, there is a complete change in the pattern of total acre inches pumped under the three water-use alternatives. Greater withdrawals in early periods under the unrestricted alternative reduces irrigation system capacity to such an extent that the lowest mean total acre inches pumped from years 12 through 20 is by the unrestricted irrigator. The second largest rate of water use during the same period occurs under the graduated tax alternative. The largest rate of water use during the period occurs under the quantity limitation simply because the pumping capacity under this alternative is not depleted as rapidly in earlier years of the simulated time period as for the other two alternatives.

All three methods of water-use regulation result in approximately the same mean number of acre inches pumped during year 20. In addition, the feet of saturated thickness remaining at the end of year 20 are 35.84, 38.37 and 37.72 for unrestricted, quantity limitation and graduated tax alternatives, respectively. Thus, though the patterns of water use exhibit considerable variation, particularly during years 1 through 12, the feet of saturated thickness remaining at the end of 20 years is approximately the same for all three alternatives.

It is not immediately obvious from Figure 6 whether the mean acre inches pumped over the 20-year period differ significantly under alternative methods of water-use regulation. This question can best be answered by testing the difference in means for statistical significance, rather than by making subjective evaluation based on the graphs in Figure 6. The Wilcoxon Matched-Pairs, Signed Ranks Test is a powerful nonparametric test that may be used to test whether two related groups differ significantly [102, pp.

75-83]. A detailed discussion of the Wilcoxon Matched-Pairs, Signed Ranks Test is included in [61, pp. 275-277].

Statistical tests between each set of mean values of total acre inches pumped under the three institutional alternatives reveal no significant differences among any of the distributions at the five percent level. Thus, even though Figure 6 indicates a seemingly large difference in acre inches pumped from year 3 through 7 under the unrestricted and quantity limitation alternatives, the means are not significantly different, from a statistical standpoint.

Since timeliness of application in relation to critical stages of plant development is more important to final yield and net returns than is the total number of acre inches applied, the possibility of significant differences among net farm income and net worth means still exists.

Net Farm Income

Mean values of net farm income over the 20-year period under unrestricted, quantity restriction and graduated tax alternatives are presented graphically in Figure 7. Several outstanding features merit attention. By far the most important is that net farm income

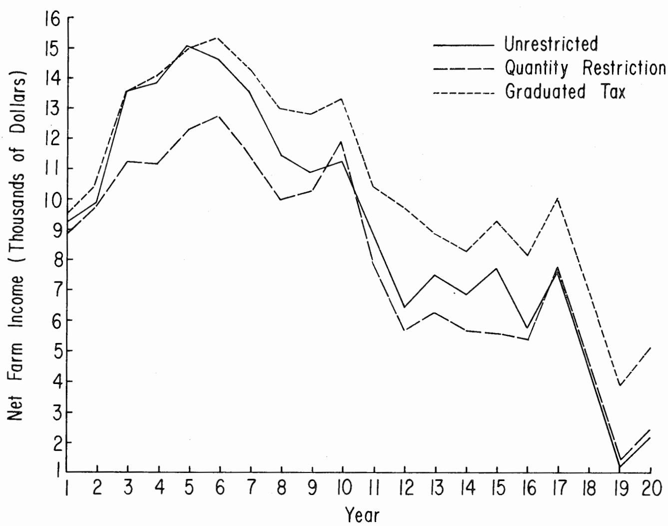

Figure 7. A Comparison of Mean Net Farm Income Under Alternative Water-Use Regulation Methods for Resource Situation 1

under the graduated tax alternative exceeds net farm income under the unrestricted pumping alternative during every year except year 5. From year 1 through year 5, net farm income under both alternatives increases and the level of net farm income is approximately the same for both. Beginning with year 6, net farm income under the graduated tax alternative exceeds net farm income under unrestricted pumping by a wider margin.

Several interrelated factors create this phenomenon. First, the unrestricted irrigator tends to operate his irrigation system at its maximum capacity. In responding to soil moisture levels throughout the growing season, the tendency is to apply more water than is profitable. By reducing applications of water during some periods, applying water on grain sorghum during irrigation period 4 only if it is profitable and insuring a preplant irrigation of wheat every year, the irrigator operating under the graduated tax alternative is able to pay the tax and still achieve higher net farm income.

A second factor contributing to higher net farm income under the graduated tax alternative is that less water is pumped during earlier periods thus enabling the taxed irrigator to achieve more timely irrigations in relation to plant needs during later critical periods of development. More timely applications lead to higher final yields for the same amount of irrigation water. Since pumping costs rise more slowly, net returns per acre and net farm income are higher. A third related factor is that higher yields are reflected in higher government payments, particularly from years 11 through 20, for the irrigator under the graduated tax alternative. Higher government payments contribute directly to higher net farm income.

Net farm income under the quantity restriction is of interest also. It is lower than net farm income under the graduated tax during every year and exceeds net farm income under unrestricted pumping conditions during year 10 and from year 17 through year 20. Net farm income under unrestricted and quantity restriction alternatives are almost identical from year 16 through 20, however, higher remaining pumping capacity enables the quantity restriction alternative to maintain a higher net farm income during this period.

An analysis of Figure 7 suggests that mean net farm income under the graduated tax alternative differs significantly from mean net farm income under a quantity restriction. This hypothesis, among others, was tested through the use of the Wilcoxon Matched-Pairs, Signed Ranks Test. Three tests were conducted on mean values of net farm income. All three allow us to reject the null hypothesis of no difference between the mean values of net farm income at the .01 probability level. Mean net farm income under the graduated tax alternative is above that under either the unrestricted pumping or quantity limitation alternatives. Mean net farm income under unrestricted pumping is above that under the quantity limitation.

Figure 8 illustrates the effects of the three water-use regulatory alternatives on variability of net farm income, as measured by the coefficient of variation. The coefficient of variation is expressed as

$$(5)\ cv = s/\bar{x}$$

where cv represents the coefficient of variation; s represents standard deviation; and $\bar{x}$ represents the mean. The coefficient of variation affords a valid comparison of the variation among large values, such as income in initial periods, and variation among small values such as income in later periods [80, p. 64]. The coefficient of variation resulting from a quantity restriction on water use is consistently higher from year 1 to year 18.

This is not an unexpected result. The quantity restriction is often reached during irrigation period 4 when grain sorghum is in the boot-heading and grain-filling stages of plant development. Failure to apply needed moisture during this period reduces final yield

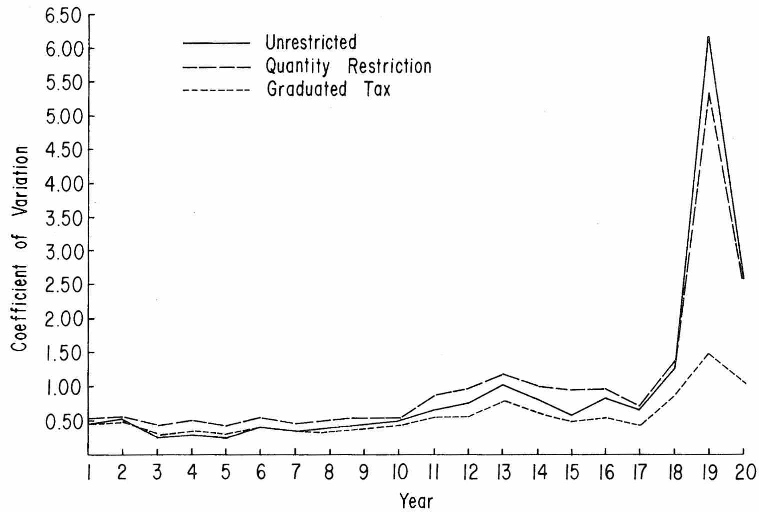

Figure 8. A Comparison of Coefficients of Variation of Net Farm Income Under Alternative Water-Use Regulation Methods for Resource Situation 1

unless natural rainfall is sufficient to compensate for the lack of irrigation water. In addition, when the quantity restriction is reached, preplant irrigations on irrigated wheat are eliminated. The existence of a stand on wheat is then determined by Fall soil moisture conditions. About 20 percent of the time no stand is achieved and wheat yield is assumed to be zero. Both of the above factors combine to increase variability of net farm income relative to mean net farm income under the unrestricted and graduated taxation alternatives.

Coefficients of variation of net farm income under the unrestricted and graduated tax alternatives are approximately the same for the first few years of the simulated time period. Coefficient of variation for unrestricted pumping is larger than that of the graduated tax for year 2, approximately equal during years 6 and 7, and then is larger for years 8 through 20. Thus, after year 7, the coefficient of variation for the graduated tax alternative is lower than for either the unrestricted or quantity restriction alternatives.

The marked increase in coefficients of variation during years 18, 19 and 20 reflects the declining pumping capacity, declining proportion of irrigated acres and increased variability resulting from dryland production. Extreme variability occurring in year 19 relative to years 18 and 20 results from the random occurrence of very dry years across replications of year 19. The reduced variability under the graduated tax alternative results from timely applications of irrigation water during irrigation periods 4 and 5. These applications stabilize wheat and grain sorghum yields, and government payments, thus reducing variability of net farm income.

Net Worth

Mean values of net worth over the 20-year simulated time period under unrestricted, quantity restriction and graduated tax alternatives are presented in Figure 9. Graphs of the three sets of means leave no doubt that net worth under the graduated tax alternative is higher throughout the period. Net worth under the unrestricted alternative is second largest over the 20-year period followed by net worth under the quantity limitation alternative. The differences appear significant, particularly after about year 10. The means were tested for statistical significance using the Wilcoxon Matched-Pairs, Signed Ranks Test. Application of the testing procedure substantiates this intuitive conclusion [61, pp. 169-171].

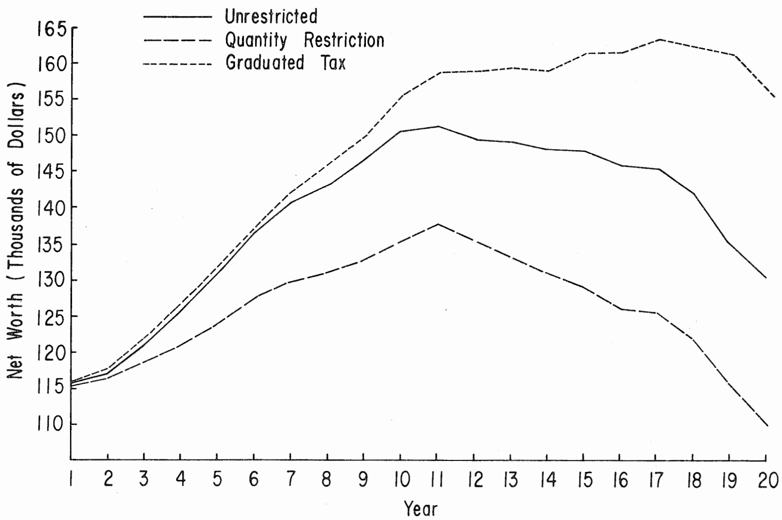

Figure 9. A Comparison of Mean Net Worth Under Alternative Water-Use Regulation Methods for Resource Situation 1

Statistical Comparisons of Unrestricted Pumping, a Quantity Limitation and a Graduated Tax on Resource Situation 2

Resource Situation 2 represents the adequate water situation within the study area. The weighted average saturated thickness of the underground formation is 325 feet. Since only about 125 feet of saturated thickness are required to maintain an irrigation system pumping capacity of 1,000 g.p.m., irrigation operators may lower the static water level by approximately 200 feet before well yields begin to decline and a significant rise in pumping costs occurs. Thus, no expansions in the number of irrigation wells or irrigated acres are assumed for representative firms in Resource Situation 2.

Results of the simulation of unrestricted pumping, a quantity limitation and a graduated tax on Resource Situation 2 are presented in detail in the appendix and are summarized below:

Acre Inches Pumped

Figure 10 illustrates the effect on total acre inches pumped for each water-use regulatory alternative. Several features are obvious

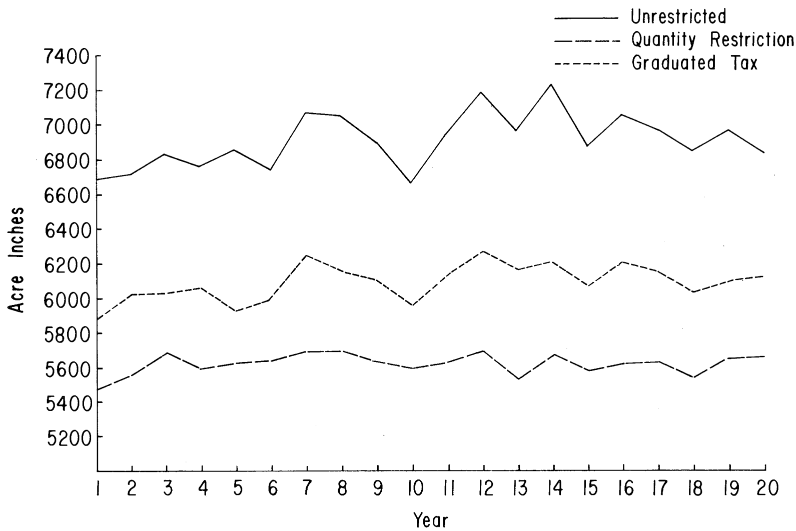

Figure 10. A Comparison of Mean Acre Inches of Irrigation Water Pumped Under Alternative Water-Use Regulation Methods for Resource Situation 2

at first glance. First, the number of acre inches pumped under the unrestricted alternative exceed total acre inches pumped under the graduated tax alternative by a wide margin. Second, acre inches pumped under the graduated tax alternative likewise exceed acre inches pumped under the quantity restriction by a wide margin. Third, there is considerably more variability associated with the unrestricted alternative. Of the three alternatives, the quantity restriction has the smallest variation in total acre inches pumped, as expected.

Of critical importance to policy makers is whether the three water-use regulatory alternatives differ with respect to total acre inches pumped from a statistical standpoint. To answer this question, mean values of total acre inches pumped over the 20-year period are tested for significant differences using the Wilcoxon Match-Pairs, Signed Ranks Test.

A detailed discussion of the hypothesis tested in each case, the critical level and the computed value of the statistic is reported by Mapp [61, pp. 195-196]. The tests reveal a significant difference between mean values of acre inches pumped for the unrestricted pumping versus quantity limitation alternatives, unrestricted pumping versus graduated tax alternatives and graduated tax versus quantity limitation alternatives. Referring to Figure 10 statistical tests reveal that each set of means of total acre inches pumped is above the set or sets of means underlying it.

Net Farm Income

A graphic presentation of mean net farm income over a 20-year period under unrestricted, quantity restriction and graduated taxation alternatives appears in Figure 11. The graph illustrates the effect on net farm income of increased yields and increasing government payments over the initial five years of the simulated time period. From year 5 through year 20, the increase in net farm income is moderate, reflecting gradual retirement of chattle and real estate debts and accumulation of cash in excess of the $10,000 minimum specified at the beginning of the simulation analysis.

The level of farm income under the graduated tax alternative is only slightly less than under unrestricted pumping. Both unrestricted pumping and the graduated tax alternative have levels of net farm income which greatly exceed the level under the quantity restriction. Based on the graphic analysis, three statistical tests are conducted to test three hypotheses. The first test conducted is to determine whether or not significant differences exist between mean net farm income under unrestricted pumping

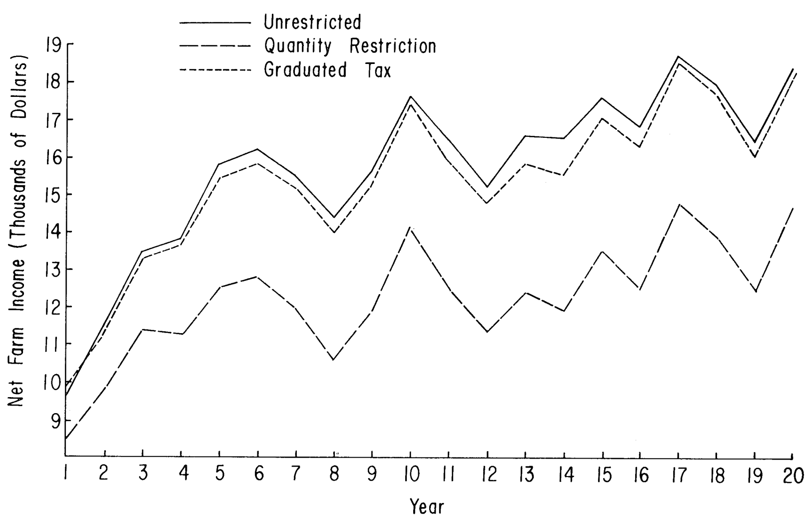

Figure 11. A Comparison of Mean Net Farm Income Under Alternative Water-Use Regulation Methods for Resource Situation 2

and the quantity restriction. The second test conducted is to determine whether or not a significant difference exists between mean net farm income under the graduated tax alternative and a quantity restriction on pumping. The final statistical test concerning net farm income tested the null hypothesis of no difference between the mean under unrestricted pumping and the mean under graduated taxation.

For Resource Situation 2, the three statistical tests substantiate that mean net farm income under unrestricted pumping exceeds that under either the graduated tax alternative or the quantity limitation. The mean under a graduated tax is significantly larger than under the quantity limitation.

A comparison of Figures 10 and 11 reveals that the difference between mean acre inches pumped over the 20-year period for unrestricted pumping versus graduated taxation is greater than the difference between corresponding means of net farm income. That is, irrigators pumping without restrictions tend to apply irrigation water to the point where its marginal value product is very low. Thus, the irrigator operating under graduated taxation is able to apply significantly less water, pay the tax on additional water pumped above the quantity limitation and achieve a level of net farm income which appears reasonably close to that achieved under unrestricted pumping. From a policy maker's standpoint, the graduated tax might appear preferable to unrestricted pumping since it reduces pumping significantly while maintaining net farm income at a reasonable level. The farmer would prefer to pump without restrictions, not only because of the additional freedom afforded by that alternative, but because net farm income is larger.

The quantity restriction results in significantly lower total acre inches pumped and lower net farm income than the other two alternatives. Variability of net farm income is much greater than under the other two alternatives. The quantity restriction is likely to be the least preferred alternative by irrigators in the area. Policy makers wishing to pursue this alternative must build their case by evaluating two important factors. (1) The quantity limitation lengthens the life of the aquifer and provides a longer, though lower stream of net income. (2) Unrestricted pumping shortens the economic life of the aquifer and thus provides a shorter, higher stream of net farm income for individual irrigators. By discounting the streams of net returns over the life of the aquifer under alternative policies, a rational economic decision can be made. The life of the aquifer is not projected in this analysis. However, a discounting model is utilized in a subsequent section to compare net income streams under alternative policies over the 20-year span of this analysis.

Figure 12 compares relative variability of net farm income in terms of the coefficient of variation. As expected, coefficients of variation hold the opposite relationships of levels of net farm income. That is, the quantity restriction on water use results in the greatest relative variability of net farm income. The unrestricted water-use alternative results in the lowest relative variability in net farm income, with the graduated tax alternative falling between the two.

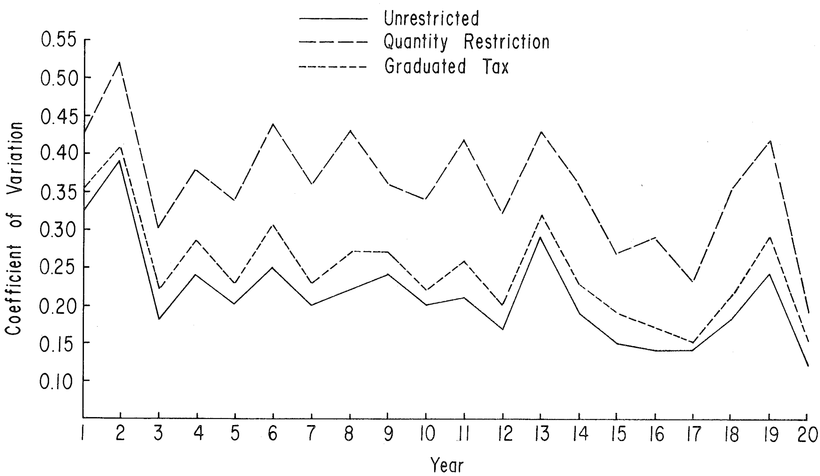

Figure 12. A Comparison of Coefficients of Variation of Mean Net Farm Income Under Alternative Water-Use Regulation Methods for Resource Situation 2

Net Worth

Figure 13 presents the mean values of net worth over the 20-year simulation period graphically. Net worth increases almost linearly, but at a slightly increasing rate, for all three water-use alternatives. Net worth levels under unrestricted pumping and graduated taxation are nearly identical and both exceed net worth under the quantity restriction by a large margin. Application of the Wilcoxon Matched-Pairs, Signed Rank Test to the mean values of net worth data indicates mean net worth for both unrestricted pumping and the graduated tax differ significantly from mean net worth under a quantity limitation. Also the two former means differ significantly from one another.

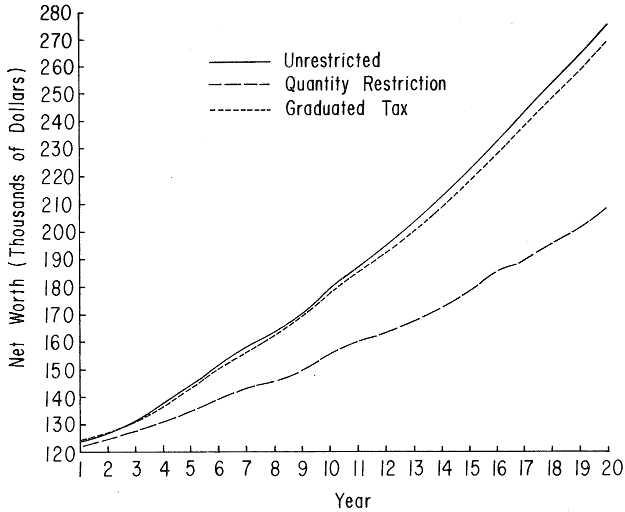

Figure 13. A Comparison of Mean Net Worth Under Alternative Water-Use Regulation Methods for Resource Situation 2

Relative Rates of Water Withdrawal for Each Water-Use Alternative

Table 8 summarizes saturated thickness remaining at the end of the 20-year simulation run. For Resource Situation 1, the mean values of feet of remaining saturated thickness are 35.84, 38.37 and 37.72 for unrestricted pumping, quantity restriction and graduated tax alternatives, respectively. Water is used at different rates for each alternative. That is, unrestricted pumping results in more rapid pumping in early periods and slower withdrawals, due to declining pump capacity, in later periods. The quantity restriction results in lower rates of withdrawal in early periods, but higher rates in later periods because greater pumping capacity remains for the irrigation system.

Pumping or withdrawal rates for the graduated tax alternative remain between those for the unrestricted and taxed alternatives. Regardless of the alternative utilized, the ending position is approximately the same. The individual either completely returns to dryland farming oı is maintaining about 80 acres of irrigated grain sorghum and attempting to spread fixed costs of the irrigation system over 40 to 65 acres of irrigated wheat during portions of the crop year not devoted to intensive irrigation of summer crops. The

Table 8. Remaining Saturated Thickness of Ogallala Formation at the End of 20-Year Simulation runs

	Resource Situation 1			Resource Situation 2		
Replication	Number Restrictions	Quantity Limitation	Graduated Tax	Number Restrictions	Quantity Limitation	Graduated Tax
Mean	35.84	38.37	37.72	235.03	251.81	245.61
Maximum	37.53	41.57	40.97	240.62	254.26	249.19
Minimum	33.42	36.08	34.67	230.49	250.82	242.88
Range	4.11	5.49	6.30	10.13	3.44	6.31
Av. Feet Decline	64.16	61.33	62.28	89.97	73.19	79.39
Av. Decline/Year	3.21	3.07	3.11	4.50	3.66	3.97

decline in saturated thickness is 64.16, 61.33 and 62.28 feet for the unrestricted, quantity restriction and graduated tax alternatives, respectively. The average decline is 3.21, 3.07 and 3.11 feet per year for the three alternatives. From the standpoint of the underground water supply, all alternatives will lead to economic exhaustion within Resource Situation 1 in about 20 years, given the assumptions of the model.

Based on water-use rates in Resource Situation 1, there is little reason for policy makers to restrict water use with a quantity limitation of 1.5 acre feet per acre of water rights. It results in lower levels of net farm income while depleting the water supply at approximately the same point in time as for the other two alternatives. The policy maker might lean toward a graduated tax if water-use regulation is deemed desirable. Higher levels of net farm income are due primarily to individual action to restrict water use in earlier periods of the crop year, and to utilize economic decision rules in allocating water once the quantity limitation has been reached.

One might argue against any type of water restriction in the poor water situation on the grounds that rational irrigators merely need to be informed that applying economic decision rules in the allocation of water can lead to higher levels of net farm income. An educational program to encourage voluntary application of rational economic decision rules to allocating the existing water supply would be more palatable to individual operators as well as to policy makers within the study area. The model developed in this study is capable of providing information regarding various irrigation strategies and their impact on net farm income.

Table 8 also presents feet of remaining saturated thickness for each water-use alternative for Resource Situation 2. Mean levels of saturated thickness are 235.08, 251.81 and 245.61 for the unrestricted, quantity restriction and graduated tax alternatives. The feet decline in saturated thickness are 89.97, 73.19 and 79.39 for the three water-use alternatives, respectively.

An 89.97-foot decline in saturated thickness for the unrestricted alternative is an average of about 4.50 feet per year. With approximately 110 feet of saturated thickness before well yields begin to decline, the unrestricted irrigator in Resource Situation 2 may be able to pump for an additional 24 years (a total of 44 years) before encountering significant changes in pumping capacity, and for perhaps an additional 35 years (a total of 55) before facing a reduction in irrigated acres.

The graduated tax alternative results in a 79.39-foot decline in saturated thickness, averaging 3.97 feet per year. At the end of 20 years, approximately 121 feet of saturated thickness remain before well reductions begin to occur. If the water table continues to decline at 1.97 feet per year, an irrigator in Resource Situation 2, operating under the graduated tax alternative, may be able to pump an additional 30 years (a total of 50 years) before well yield declines commence, and for perhaps an additional 41 years (a total of 61 years) before facing a reduction in irrigated acreage.

Pumping under a quantity restriction results in a decline of 73.19 feet in saturated thickness for an average of 3.66 feet per year. Almost 127 feet of saturated thickness remain before yield reductions begin. If the water table continues to decline at a rate of 3.66 feet per year, perhaps 35 years (a total of 55 years) of pumping remain before the irrigator in Resource Situation 2, pumping under a quantity restriction, is faced with declining well yields and rising pumping costs. Perhaps an additional 46 years (a total of 66 years) pumping exists before any reduction in irrigated acreage is necessary.

These statements apply strictly to the individual irrigator with a beginning saturated thickness of 325 feet, depth to water of 125 feet, well depth of 450 feet and pump depth of 400 feet. They also assume the irrigator is pumping from a closed basin one section in size with a given 1,000 g.p.m. well and constant production organization. One must exercise great care when extrapolating from the assumed situation to all irrigators who are classified in Resource Situation 2. Some individuals in Resource Situation 2 have just above 200 feet of saturated thickness and experience an impact on well yield and pumping cost before 20 years have expired, assuming a decline of 4.5 feet per year in saturated thickness. Other individuals in Resource Situation 2 have perhaps 500 feet of saturated thickness and a seemingly endless water supply. At least, barring extraordinary and unforeseen circumstances, their water supply is sufficient for this generation. Thus, statements regarding the water situation for Resource Situation 2 must be viewed as applying to the modal representative farm firm defined for this study. Considerable variation exists among individual operators. Unfortunately, only a limited number of situations could be simulated with the available funds.

Discounting Net Income Streams to Their Present Value

The streams of net farm income resulting under the unrestricted, quantity restriction and graduated tax alternatives are discounted to their present value at several interest rates. Present values of net farm income for each regulatory alternative at four different interest rates for Resource Situations 1 and 2 are presented in Table 9.

The discounting model is appropriate because income in the current time period is worth more than income in future time periods due to uncertainty about the future and a preference by most individuals for current rather than future income. Through time, the discounting factor, $\frac{1}{(1 + i)^n}$ increases. Thus, the value of future net income is reduced relative to the value of current net income. The magnitude of present values increases as interest rates decline because the discounting factor declines with the interest rate. Thus, the value of net income, when discounted, is larger.

Implications to be drawn from the analysis do not vary with interest rates. For Resource Situation 1, present value of net income is greatest for the graduated tax alternative. This finding is not surprising since net farm income under the graduated tax alternative exceeds net farm income under the unrestricted pumping alternative during every year but one. Present value of net farm income under unrestricted pumping exceeds that under the quantity limitation. Net farm income under unrestricted pumping greatly exceeds net farm income under a quantity restriction during early years of the simulated time period. During early years, the discount factor is small, and discounted values of net farm income large. It is only during year 10 and years 17, 18, 19 and 20 that net farm income under a quantity restriction slightly exceeds net farm income under unrestricted pumping. In late periods, the discount factor is large, and contributions to the present value of net farm income by these excesses of income under a quantity restriction over income under unrestricted pumping are small.

For Resource Situation 2, the present value of net farm income under unrestricted pumping exceeds present values under both graduated taxation and a quantity limitation. This result is expected since the level of net farm income under unrestricted pumping exceeds that under the graduated tax every year except year 1. Since the levels of net farm income remain homologous over time, the present values are nearly the same. Present values of net farm

Table 9. Present Value of Net Farm Income for Three Water-Use Regulation Alternatives at Four Interest Rates

	Resource Situation 1 Water-Use Regulation Alternative			Resource Situation 2 Water-Use Regulation Alternative		
Interest Rate	No Regulation	Quantity Limitation	Graduated Tax	No Regulation	Quantity Limitation	Graduated Tax
.08	101,264	89,695	112,843	155,056	124,868	151,760
.05	123,421	109,469	139,711	200,776	160,733	196,366
.03	142,643	126,696	163,444	242,817	193,728	236,743
.01	166,761	148,392	193,694	298,321	237,257	291,736

income under both unrestricted pumping and graduated taxation exceed present value of net farm income under the quantity limitation. This finding is consistent with the significant differences found between distributions of net farm income under unrestricted pumping and graduated taxation when tested against the distribution under the quantity restriction.

Based on computation of present values of net farm income over the 20-year simulated time period, one can conclude that the timing aspects of the streams of net farm income do not differ enough for the implications of this analysis to be changed. A more valid basis of comparison would be to compute the present value of the longer, smaller stream of net farm income under the quantity restriction and compare it with a shorter, larger stream resulting under unrestricted pumping. Unfortunately, this study does not lend itself to that type of analysis.

Summary and Conclusions

Growth of irrigation within the Central Basin of the Ogallala Formation has progressed rapidly during the past decade. Future development is expected to continue at a rapid rate. The Central Basin is essentially a closed container of water. Additions to the water supply occur only as a result of percolation of rainfall and irrigation water into the aquifer. Average annual recharge is negligible relative to current withdrawals. Thus, over time, the quantity of water within the Central Basin is being depleted by the actions of individual irrigators.

The Ogallala Formation is not a uniform aquifer. Depth to water and saturated thickness are quite variable within the Central Basin. As the water table declines, the effects of declining well yields and rising pumping costs on profitability of irrigated crop production are expected to vary widely from area to area within the aquifer. Estimates of the impact of continued depletion of water supplies on individual farm firms in different resource situations are not available.

The finite quantity of water in the Central Basin of the Ogallala Formation is a stock resource possessing many of the characteristics of commonality. It is a stock resource because its total quantity does not increase with time. Commonality problems arise because all irrigators pump from a common source and each has his own self interests in mind. Individuals act to maximize returns to the scarce water resource from year to year without reference to future years. The collective actions of all irrigators increase future pumping costs and reduce the availability of future water supplies. Current water laws do little or nothing to discourage water use. Since the increased cost of pumping must be borne partly by all irrigators pumping from the basin, there is a divergence of private and social costs.

Several courses of action are available in the light of divergent social and private costs. One is to ignore the divergence of costs, allow current rates of water application to continue and deplete the water supply at a rapid rate. A second course of action is to more closely align social and private costs by restricting the quantity of water each irrigator is allowed to pump during a crop year. A third course of action to more closely align private and social costs is to levy a graduated tax per unit above the quantity limitation. Other courses of action are available, but this study is limited to consideration of the above three.

One example of each of the three courses of action was simulated in this study. The first alternative is continued development and pumping without restrictions. This alternative assumes irrigators base irrigation decisions on the level of available soil moisture and provides no incentive to conserve water use at the current time for future use. The second alternative simulated requires irrigators to restrict pumping to 1.5 acre feet per acre of water rights. Rather than pumping strictly on the basis of available soil moisture, the irrigator is assumed to reduce pumping in early periods of the crop year to a specified maximum number of acre inches per crop per period. This reduction in pumping during irrigation periods early in the year acts as a hedge against the uncertainty of weather conditions during later periods of the crop year. The third water-use regulatory alternative simulated allows the irrigator to pump as much irrigation water as desired, however, once the previously mentioned quantity limitation is reached, additional acre inches may be pumped only if the irrigator is willing to pay $0.50 per acre inch for each acre inch pumped above the quanity limitation. The irrigator is assumed to follow the rules specified under the quanity limitation alternative until that limit is reached. Then additional applications are made if the value of yield reductions which will occur, projecting current moisture conditions, exceeds the cost of the additional irrigation, including added harvesting and hauling, pumping, labor and tax costs. Each alternative was simulated for a

640-acre farm with 315 acres of irrigated crops for each of two resourced situations.

Resource Situation 1 represents the "poor water" situation within the study area. It was assumed the weighted average saturated thickness of 100 feet will support a well yield of approximately 780 g.p.m. Well yields decline rapidly over time causing the operator to add a second and third well, and then reduce the number of acres devoted to irrigated crop production as it becomes uneconomic to irrigate the entire acreage. The effects of unrestricted pumping, quantity limitation and graduated taxation on total acre inches pumped, net farm income and net worth for the irrigators in Resource Situation 1 were evaluated.

An analysis of the simulation results indicates that the total acre inches pumped over the 20-year period under the three institutional alternatives do not differ significantly. However, the distribution of water use over the 20-year planning horizon does differ to some extent. The unrestricted irrigator pumps more water during early years of the 20-year period, depleted his pumping capacity rapidly and pumps the smallest number of acre inches in years 12 through 20. The quantity limitation results in fewer acre inches pumped during early years, but leaves the irrigator the capacity to pump the greatest number of acre inches per year from years 12 through 20. Water use under the graduated tax alternative is between the two extremes. The three water-use alternatives, though differing somewhat in timing of applications, result in essentially the same saturated thickness and decline in the water table at the end of the 20-year period. The average feet of saturated thickness remaining after 20 years of operation are 34.8, 38.4 and 37.7 for the unrestricted, quantity restriction and graduated tax alternatives, respectively.

Mean net farm income under the graduated tax alternative is significantly above mean net farm income under unrestricted pumping and a quantity limitation. Also the mean under unrestricted pumping is significantly larger than the mean under a quantity restriction on water use. The somewhat surprising conclusion that mean net farm income under the taxing alternative is greater than under unrestricted pumping results from more rational use of irrigation water when a tax on additional use is imposed. The taxed irrigator achieves more timely irrigation in relation to plant needs and higher crop yields for the same amount of water. Since pumping costs rise more slowly, net returns per acre and net farm income are higher despite the tax payments. It is also significant to note that the variability of net farm income as measured by the coefficient of variation is greatest under the quantity restriction and least under the graduated tax alternative.

The mean net worth of the firm under graduated taxation also exceeds the mean net worth under unrestricted pumping or the quantity limitation. This is not surprising given the results concerning net farm income above. Mean net worth with unrestricted pumping exceeds that under the quantity limitation.

Resource Situation 2 represents the "adequate" water situation within the study area. The weighted average saturated thickness of the Ogallala Formation for this resource situation is 325 feet — a sufficient saturated thickness to maintain a pumping capacity of 1,000 g.p.m. throughout the 20-year planning horizon. Irrigators in this situation experience some increase in pumping costs as the water table declines, but are neither required to add additional wells to maintain their pumping capacity nor to revert a portion of their acreage to dryland production over the 20-year period.

The effects of unrestricted pumping, quantity limitation and graduated tax alternatives on total acre inches pumped, net farm income and net worth for the representative firm were simulated over a 20-year period. Operation with the unrestricted alternative allows the irrigator to pump at the capacity of the system for the entire growing season and thus pump significantly more water than the firm operating under either the quantity limitation or the graduated tax. The amount of water pumped under the graduated taxation alternative is significantly greater than the amount pumped under the quantity limitation. Since capacity does not decline over time, the firm has the same ability to pump water during the latter years of the planning horizon as during the initial years. The amount of water pumped per year does vary depending on the weather conditions simulated for the year. Variability of acre inches pumped is greater under the unrestricted pumping alternative. The least relative variability is observed under a quantity limitation because the irrigator is prohibited from pumping more than the upper limit, even during very dry years.

Discounting the streams of net farm income to their present values at one, three, five and eight percent does not change the general conclusions based on the undiscounted patterns of net farm income. For Resource Situation 1, the present value of net farm income is geatest under graduated taxation, followed by unrestricted pumping and the quantity limitation, regardless of the interest rate used. For Resource Situation 2, the present value of net farm income under restricted pumping exceeds present values under both graduated taxation and a quantity limitation. Likewise, the present value of net farm income under graduated taxation exceeds that under the quantity limitation. Thus, the difference in the time path of net farm income resulting from the different water-use alternatives is not great enough over the 20-year time span to alter the implications of the analysis.

Policy implications differ somewhat for the two Resource Situations. In Resource Situation 1, the poor water situation, economic exhaustion appears likely in about 20 years regardless of the water-use policy adopted. Policy makers interested in conserving water may be indifferent as to whether pumping continues unrestricted or is reduced in initial periods by applying a graduated tax or quantity limitation. However, policy makers are also interested in the level of income that may be maintained if water-use is restricted. This analysis indicates that the level of net farm income and net worth are significantly greater under the graduated taxation alternative than under either unrestricted pumping or a quantity limitation. For this reason, the policy maker might prefer imposition of a graduated tax on water-use. A complicating factor is that the current legal framework within the study area does not lend itself to imposition of taxes on water-use. Laws would have to be changed. Restriction of water-use through taxation requires a significant change from a strict interpretation of the Doctrine of Prior Appropriation.

Individual irrigators are likely to prefer unrestricted pumping despite some evidence that the graduated tax alternative may lead to higher net farm income. One factor should be emphasized. The primary reason the graduated tax results in greater net farm income, while utilizing essentially the same quantity of water, is that it provides an incentive for irrigators to reduce excessive pumping in early periods of the crop year and apply an economic decision rule in allocating water during Irrigation Periods 4 and 5. It may be argued that no water restrictions are needed for irrigators in Resource Situation 1. Perhaps irrigators merely need to be informed that application of economic decision rules in allocating water to maximize net returns, rather than crop yields, can lead to higher levels of net farm income. An educational program of this nature would be more palatable to individual operators as well as policy makers within the study area.

Restriction of water-use for Resource Situation 2 has a different impact and somewhat different policy implications of the alternatives studied. Unrestricted pumping results in the greatest water use, highest level of net farm income and net worth and lowest relative variability of net farm income. For the individual irrigator, unrestricted pumping provides the most favorable set of conditions. However, unrestricted pumping depletes the water supply more rapidly than either the graduated tax or quantity limitation alternatives.

The analysis indicates that the graduated tax alternative reduces water use significantly while maintaining a level of net farm income comparable to that under unrestricted pumping. Imposition of the graduated tax requires significant changes in the legal and institutional framework and may prove difficult to enact and administer. However, significant revenue may be generated from this alternative.

Policy makers have an additional alternative. The quantity limitation provides the lowest level of net farm income with the greatest relative variability. However, water-use rates are reduced by the largest amount also. Policy makers wishing to pursue this alternative have the legal basis already in existence. The economic feasibility rests upon answers to several important questions. First, how much will the quantity limitation lengthen the life of the aquifer? Second, what is the present value of the longer but lower stream of net farm income? Third, what will the length of the economic life of the aquifer be under unrestricted pumping? Fourth, what is the present value of the shorter, higher stream of net farm income under unrestricted pumping? This analysis does not project the life of the aquifer under alternative policies. However, based upon some linear projections of water use rates under the three policies, the maximum difference between the time of significant well yield reductions under the policy of most rapid depletion (unrestricted pumping) and the policy of slowest depletion (a quantity limitation) is only about 11 years. This 11 years is the difference between a total of 55 years under the quantity restriction and 44 years under unrestricted pumping. Policy makers may find it difficult to convince individual farmers in the area to forego almost certain income in the current period for the prospect of uncertain income from 44 to 55 years in the future. Thus, policy makers may find it difficult to make a convincing case for water-use regulation in Resource Situation 2.

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APPENDIX

Detailed Results of Simulating Alternative Methods of Water-Use Regulation

The initial portion of this appendix presents a detailed summary of the effects of unrestricted pumping on the representative farms and water supply in Resource Situations 1 and 2. Subsequent parts summarize the effects of a quantity limitation and a graduated tax above the quantity limitation on the representative farms and water supply in each resource situation.

Effects of Unrestricted Water Use on Resource Situation 1

Resource Situation 1 represents the poor water situation for the study area. Average saturated thickness of the underground aquifer is 100 feet. This amount of saturated thickness will support a well yield of approximately 780 g.p.m. Assumptions concerning the number of acres irrigated, acreage planted to each crop, and the decision rules followed to drill additional wells and revert acreage to dryland are discussed in the previous section. Operation of the representative firm under each method of regulation was simulated over a 20-year time horizon and each method of regulation was replicated 15 times. The results of the simulation analysis are presented below.

Acre Inches pumped

The effect of unrestricted water use on the quantity of water pumped through time is shown in Table 10. The mean, standard deviation, maximum, minimum and range have been computed

Table 10. Summary of Total Acre Inches Pumped, Net Farm Income and Net Worth for Resource Situation 1 With no Restrictions on Water Use[a]

	Year																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Total Acre Inches Pumped																				
Mean	5805	5550	6911	7385	7061	6585	6446	5935	6006	6218	5898	5361	4610	4028	3280	2859	2486	2208	1963	1324
Std. Dev.	972	500	1632	1265	1094	686	323	426	754	846	503	561	539	555	472	575	377	406	565	982
Maximum	6699	6039	8305	9265	8229	7607	7092	6704	7568	7492	6506	6195	5161	4949	4143	3827	3419	2739	2361	2202
Minimum	2852	4225	1923	4704	4454	5369	5605	5167	4981	4490	4646	4136	3261	2858	2561	1760	1819	903	0	0
Range	3847	1815	6382	4561	3776	2238	1486	1542	2587	3002	1861	2059	1901	2091	1592	2066	1600	1837	2361	2202
Net Farm Income																				
Mean	9019	9809	13546	13839	15045	14624	13593	11454	10870	11324	8780	6405	7502	6838	7719	5714	7503	4351	1031	2183
Std. Dev.	4151	5470	3462	4452	3957	5840	4700	4489	5051	5775	5761	4851	7620	5666	4591	4797	4930	5453	6503	5639
Maximum	15567	22925	20868	21891	23876	24824	23607	19976	21111	20037	19987	16314	22603	14697	18372	11547	15699	10238	11113	11924
Minimum	3397	2714	8850	7947	9571	4581	3261	4568	3300	2996	902	-3534	-8629	-309	2466	-3668	571	-8407	-9883	-8109
Range	12170	20211	12018	13944	14305	20243	20346	15408	17811	17041	19085	19848	31232	15006	15906	15215	15128	18645	20996	20033
Coef. of Var.	0.46	0.56	0.26	0.32	0.26	0.40	0.35	0.39	0.46	0.51	0.66	0.76	1.02	0.83	0.59	0.84	0.66	1.25	6.31	2.58
Net Worth																				
Mean	120792	121923	126075	130517	135829	141397	145683	148152	151717	155568	156182	154778	154237	153286	152979	150822	150268	146852	140219	135555
Std. Dev.	3334	5673	7259	9347	10140	13568	15926	17393	17780	21031	23995	27241	30219	32832	34975	38402	41421	44527	48768	52346
Maximum	126009	135524	143124	154176	160580	167980	171284	172769	175885	182686	181628	186824	198840	198111	201896	203823	208574	210251	213980	214774
Minimum	116195	113631	115735	119604	125187	122641	123589	122553	125468	122706	118326	111788	96592	88783	84606	74377	67422	59749	47057	36537
Range	9814	21893	27389	34572	35393	45339	47695	50216	50417	59980	63302	75036	102248	109328	117290	129446	141152	150502	166923	178237

[a] The values in this table are based on 15 replications. The values for each replication are reported by Mapp [61, pp. 130, 134 and 183].

using the 15 replications for each year of the 20-year planning horizon [61, p. 130].

The mean values in Table 10 highlight several interesting phenomena. The second irigation well is usually added at the end of the second or third crop year, and its effect on pumping capacity for the irrigation system is apparent. Average acre inches pumped increases from 5,550 in year 2 to 6,911 and 7,385 acre inches, respectively, during years 3 and 4. The third irrigation well is usually drilled at the end of either crop year 8 or 9. Increased pumping capacity is reflected through an increase in pumping from 5,935 acre inches in year 8 to 6,006 and 6,218 acre inches during crop years 9 and 10, respectively. After the third irrigation well is drilled, declines in acre inches pumped result from (1) declining well yields; (2) increasing pumping costs; and (3) the resulting reduction in irrigated acreage. Mean values decline steadily from 6,218 acre inches in year 10 to 1,324 acre inches in year 20.

The maximum number of acre inches pumped during any replication of any year is 9,265 during crop year 4. A combination of excess pumping capacity after the addition of well 2 and extremely dry weather conditions during the year are primary causal factors. The minimum number of acre inches pumped during any replication of crop year 4 is 4,704.

During five of the fifteen replications all irrigated crops were converted to dryland wheat by crop year 20 and zero pumping occurred. In one of the replications conversion to total dryland farming occurred by crop year 19. Thus one-third of the fifteen replications simulated result in a return of dryland farming by the 20th year. Variable pumping costs per acre inch during the final year in which irrigated crops are raised ranged from $1.42 to $1.68 for the five replications reverting all land to dryland crop production.

Saturated thichness of the underground aquifer at the end of the 20-year simulation runs ranges from 33.42 to 37.53 feet and averages 35.84 feet. Transforming these figures into feet of decline in saturated thickness results in an average decline of 64.16 feet over the 20-year period, an average decline of 3.21 feet per year. The original 100 feet of saturated thickness underlying Resource Situation 1 contained approximately 9,600 acre feet of water which could be withdrawn for irrigation purposes.[9] The decline in saturated thickness to 35.84 acre feet leaves approximately 3,440

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9. The figure 9,600 acre feet is computed assuming 640 acres overlie the 100 feet of saturated thickness and that the specific yield of the Ogallala Formation is 0.15. Then 640 acres x 100 feet x 0.15 = 9,600 acre feet.

acre feet of water that is uneconomical to pump for irrigation purposes. Thus, of the original volume, only 35.84 percent remains at the end of the 20-year unrestricted simulation of Resource Situation 1.

Net Farm Income

Effects of water-use regulation on net farm income are of great importance to individual farm operators and to the economy of the Central Ogallala formation. Net farm income is computed in the Farm Firm Subset as the difference between gross income and gross farm expense. As used in the context of the simulation model, it represents net returns to land, operator labor, management and risk. Net farm income is computed each year of a multi-period simulation run. The simulation runs are sequential and firm financial changes are updated each year to reflect the current status of the firm.

Table 10 contains a summary of net farm income resulting from the 15 replications of a 20-year simulation of Resource Situation 1 without water-use regulation. The mean, standard deviation, maximum, minimum and range have been computed for each year of the planning horizon.

Net farm income for farms in Resource Situation 1 increases rapidly during the initial years of irrigation system expansion. From year 1 to year 5, mean net farm income increases from $9,019 to $15,045, the maximum mean value for any year of the run. The rise in net farm income over a five-year period is primarily due to increased pumping capacity which increases irrigated crop yields. Increased yields result in greater government payments, which are computed on the basis of a five-year moving average of yields for wheat and feed grains. After year 5, mean net farm income declines gradually to $10,870 in year 9, rises to $11,324 in year 10 with additional irrigation expansion, and then follows an erratic, but declining trend through year 18. Mean net farm incomes the final two years are very low reflecting several adverse conditions. (1) Declining yields and rising pumping costs contribute to declining profitability of the irrigated operation. (2) Conversion of an increasing number of acres to dryland production reduces the mean net farm income and increases variability of income. Effects of adverse weather conditions contribute to years of very low and even negative net farm income.

During the initial five years, mean net farm income rises while variablility of income, as measured by the standard deviation, declines. The income stability contributed by government payments is obvious throughout the initial and intermediate periods of the analysis. Income variability remains relatively stable across the 20-year simulation run. However, as mean net income declines in years 11 through 20, the coefficient of variation rises. The lowest coefficient of variation is 0.26 in years 3 and 5 of the 20-year simulation of net farm income. In years 18, 19 and 20, the coefficient of variation is 1.25, 6.31 and 2.58, respectively.

The maximum net farm income for any replication of any year, $24,824, occurs early in the period, year 6. The minimum net farm income of -$9,883 occurs during the later part of period, year 19. The maximum range in net farm income of $31,232 occurs during year 13. These figures emphasize the tremendous variability in net farm income that exists within the study area. Irrigation and government programs are definite stabilizing influences on net farm income. However, as the water supply is depleted, crop yields decline and dependence on dryland production increases. As the amount of government program payments declines, variable weather conditions significantly affect variability of net farm income in the poor water situation.

Net Worth

The Farm Firm Subset computes net worth of the representative firm after each year of a multi-period simulation run. Net worth is, of course, computed as the difference between total assets and total debts. Over time, assets and debts are constantly changing. Real estate and chattle debt payments are made each year until the beginning levels have been reduced to zero. An initial real estate debt of $42,000 and an initial chattle debt of $5,234 are assumed. The chattle debt is paid off in five years and the real estate debt is retired during year 15. No further real estate or chattle debts are accumulated during the 20-year simulation runs. However, other short-term loans are required periodically to maintain the cash balance required for operation of the business.

Table 10 presents a summary of net worth for representative farms in Resource Situation 1 based on 15 replications of 20-year simulation of the firm. The mean, standard deviation, maximum, minimum and range of net worth values are given for each year of the simulation run. Mean values of net worth exhibit several characteristics. (1) There is a definite trend in net worth through time. (2) The trend in net worth is not linear, but tends to follow a sigmoid pattern. (3) Net worth reaches a maximum in year 11. This maximum lags behind full irrigation development by one or two years. (4) After reaching a maximum in year 11, mean net worth for Resource Situation 1 declines steadily to year 20. Mean net worth at the end of year 1 is $120,792 increases steadily to $156,182 in year 11 and declines to $135,555 at the end of year 20.

The standard deviation of net worth increases steadily from $3,334 in year 1 to $52,346 in year 20. Relative variability, as measured by the coefficient of variation, increases steadily over time from 0.03 in year 1 to 0.15 in year 11 to 0.39 in year 20. Increasing variability is again a function of several interelated factors. (1) Declining well yields over time result in less reliance on irrigation water to stabilize crop yields. (2) The shift of crop acres from irrigated production to dryland production tends to increase variability in yields, net returns and net worth over time. (3) Despite the completely random nature of rainfall and pan evaporation events in the Production Subset, series of "wet crop years" and of "dry crop years" years appear in the simulation runs. This phenomenon has been observed and documented for a study area which encompasses a portion of the Central Ogallala Formation [38, pp. 20-24]. The existence of series of good years contribute to a high ending net worth during replications 5 and 7 ($214,744 and $199,225, respectively). Series of dry years contribute to low ending net worth during replications 6 and 14 ($40,527 and $36,537, respectively).

The maximum and minimum net worth figures both occur during year 20. A range of $178,237 exists between the maximum of $214,774 and the minimum of $36,537.

Effects of Unrestricted Water Use on Resource Situation 2

Resource Situation 2 represents the adequate water situation within the study area. The weighted average saturated thickness of the underground formation is 325 feet. Only about 125 feet of saturated thickness are required to maintain an irrigation system pumping capacity of 1,000 g.p.m. Consequently, irrigation operators represented by Resource Situation 2 may lower the static water level by approximately 200 feet before well yields begin to decline and significant rise in pumping costs occurs. Thus the well yield remains constant at 1,000 g.p.m. for the 20-year period and no additional wells are required to maintain irrigated production of 315 acres of cropland. No expansions or contractions of irrigated cropland are assumed for representative farms in Resource

Situation 2. Other assumptions are similar to the starting situation for Resource Situation 1.

Acre Inches Pumped

A summary of total acre inches pumped under the unrestricted water-use alternative is presented in Table 11. The mean, standard deviation, maximum, minimum and range of acre inches pumped are given for each year. Since well capacity remains at 1,000 g.p.m. throughout the 20-year simulated time period, there are no significant changes in system capacity as there were for Resource Situation 1. Variability in quantity of water pumped results from random variation in rainfall and evapotranspiration rather than variations in pumping capacity and number of acres irrigated.

Mean values of total acre inches pumped range from 6,662 in year 10 to 7,233 in year 14. The maximum number of acre inches pumped during any of the simulation runs is 7,925 pumped during year 11, and again during year 18. Minimum quantity of water pumped is 3,007 acre inches in year 1. The greatest range in acre inches pumped is 4,806 in year 1. The considerable variability in total acre inches pumped is one indication of the weather variablility existing in the study area and of the ability of the Production Subset to simulate these variable weather conditions.

Saturated thickness at the end of the 20-year period under unrestricted pumping ranges from a minimum of 230.49 feet to a maximum of 240.62 feet, averaging 235.03 feet. In terms of feet of decline in saturated thickness, the mean decline over 15 replications at the end of 20 years is 89.89 feet for an average rate of decline of 4.50 feet per year.

Net Farm Income

The effects on net farm income of unrestricted pumping by representative farms in Resource Situation 2 are presented in Table 11. The mean, standard deviation, maximum, minimum, range and coefficient of variation of net farm income are shown by year.

Mean values of net farm income, while fluctuating widely from year to year, have a general upward trend over the 20-year period. The rise is rapid during the first five years as the result of high crop yields per acre and a corresponding rise in government payments. Mean net farm income rises from $10,598 in year 1 to $16,754 in year 5. Over the same period, mean values of government payments

Table 11. Summary of Total Acre Inches Pumped, Net Farm Income and Net Worth for Resource Situation 2 With no Restrictions on Water Use* [a]

	Year																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	Total Acre Inches Pumped																			
Mean	6692	6711	6835	6777	6861	6743	7065	7043	6900	6662	6948	7181	6963	7233	6871	7061	6974	6843	6972	6823
Std. Dev.	1249	971	622	910	1134	806	429	739	833	795	866	635	1095	596	916	741	710	1127	846	705
Maximum	7813	7745	7474	7862	7921	7921	7670	7865	7742	7865	7925	7835	7802	7895	7685	7835	7865	7925	7791	7862
Minimum	3007	4297	5602	4770	3911	5325	6142	5878	5051	4740	4950	5681	4005	5947	4567	4791	4860	3352	5130	5227
Range	4806	3448	1872	3092	4010	2596	1528	1987	2691	3125	2975	2154	3797	1948	3118	3044	3005	4573	2661	2635
	Net Farm Income																			
Mean	10598	12434	14413	14767	16754	17192	16421	15353	16601	18563	17420	16172	17506	16974	18548	17794	19644	18908	17364	19293
Std. Dev.	3872	5526	3340	4307	4152	5243	4112	4191	4764	4613	4545	3490	5950	4022	3774	3374	3744	4423	5045	3336
Maximum	16403	24868	21941	22167	26548	26226	24518	23334	25546	26076	26156	22400	31737	23400	27602	22434	27433	26993	24284	25059
Minimum	4330	4443	9930	7454	11030	8516	7454	9988	8612	10998	10232	12213	8665	10124	13451	12118	13455	9660	9324	13491
Range	12073	20425	12011	14713	15518	17710	17064	13346	16934	15078	15924	10187	23072	13276	14151	10316	13978	17333	14960	11568
Coef. of Var.	0.37	0.44	0.23	0.29	0.25	0.30	0.25	0.27	0.29	0.25	0.26	0.22	0.34	0.24	0.20	0.19	0.19	0.23	0.29	0.17
	Net Worth																			
Mean	123260	126540	131612	137033	143829	150914	157618	163414	170317	178998	187035	194557	203181	211904	221762	231107	242128	252870	262853	274723
Std. Dev.	3087	5496	6776	8404	8697	11432	13379	14393	14915	16441	18423	20073	20889	22453	23291	24673	25219	26488	27195	27653
Maximum	127823	139113	146822	158384	164767	172328	178578	183586	190288	199919	206092	215627	230909	238398	251790	263616	276946	290089	305424	318245
Minimum	118215	117570	120917	127959	134297	134381	138461	140193	146150	152712	154236	159291	168613	174833	182991	188138	197833	204098	212925	223685
Range	9608	21543	25905	30425	30500	37947	40117	43393	44138	47207	51856	56336	62296	63565	68799	75478	79113	85991	97499	94560

[a] The values in this table are based on 15 replications. The values for each replication are reported by Mapp [61, pp. 174, 176, 178].

(wheat certificates plus feed grain payments) rise from $8,218 to $13,625. So, of the $6,156 increase in net farm income, $5,403 results from an increase in government payments. Government payments, which are computed on the basis of a five-year moving average, stabilize after year 5 and remain in the $13,200 to $13,700 range. Mean net farm income continue its upward trend as chattle debts are paid off and the beginning real estate debt is retired. Cash reserves above the $10,000 minimum specified in the Farm Firm Simulation Model earn interest also. The maximum mean net farm income is $19,644 in year 17 and mean net farm income in year 20 is $19,293.

Variability of net farm income fails to follow a definite pattern over the 20-year simulated time period. Relative variability, as measured by the coefficient of variation, ranges from a high of 0.44 during year 2 to a low of 0.17 during year 20. In general, the coefficient of variation is low, and is expected to be lower in this unrestricted simulation than for either the graduated tax or quantity limitation alternatives.

The maximum yearly value of net farm income is $31,737 generated in year 13. The minimum value of net farm income is $4,330 generated in year 1. The greatest range in net farm income levels for a single year occurs during year 13 when $23,072 is the difference between a maximum of $31,737 and a minimum of $8,665. Although variability from year to year is significant, the unrestricted pumping alternative under adequate water conditions leads to relatively stable, increasing net farm income over time.

Net Worth

Table 11 also presents the effects on net worth of unrestricted pumping for representative farms in Resource Situation 2 based on 15 replications of a 20-year simulation of the firm. The mean, standard deviation, maximum, minimum and range in net worth are given for each year of the simulation run.

Mean values of net worth increase steadily from year 1 through year 20 of the simulated time period. The minimum mean net worth is $123,260 in year 1. Maximum mean net worth is the ending net worth of $274,723. Ending net worth has a range of $94,560. This figure is the difference between the maximum ending net worth of $318,245 in replication 5 and the minimum net worth of $223,685 in replication 2. Two factors contribute to rising net worth over the 20-year period. The first is gradual retirement of chattle and real estate debt, which reduces liabilities. The second is gradual accumulation of cash assets.

Effects of a Quantity Restriction on Resource Situation 1

The second water-use regulatory alternative simulated is a limit on the quantity of irrigation water an individual is allowed to pump during a crop year. The irrigator is limited to pumping 1.5 acre feet per acre of water rights established for the representative farm firm. Water rights are assumed for 315 acres, resulting in a maximum allowable pumping of 472.5 acre feet or 5,670 acre inches per year. The model assumes the irrigator can continue pumping until the end of the day during which the quantity restriction is reached. Thus, there is some variation in pumping levels above 5,670 acre inches, despite the quantity limitation.

Acre Inches Pumped

Resource Situation 1 was simulated over a 20-year period and replicated 15 times. The mean, standard deviation, maximum, minimum and range of acre inches pumped are given in Table 12 for each year of the simulation runs.

Mean values of total acre inches pumped are relatively constant from year 1 through year 12. Slightly higher values in year 3 and in years 11 and 12 reflect the increased pumping capacity created by addition of irrigation wells 2 and 3. Irrigation well 2 is added at the end of crop year 2 and well 3 is added at the end of year 10 or 11, depending on when total system capacity falls below 750 g.p.m. Beginning with year 13, mean values of acre inches pumped decline steadily from 5,244 to 1,791 acre inches in year 20. Maximum mean acre inches pumped of 5,704 occurs during year 3 when pumping capacity of the irrigation system is greatest. Minimum pumping occurs during year 20, as expected, reflecting declining well yields and conversion of irrigated acreage to dryland wheat production. Complete conversion to dryland farming during the 20-year simulation occurs during 2 of 15 replications, or only about 13.3 percent of the time.

Maximum range in acre inches pumped for a single year is 2,975 acre inches in year 3. A total of 2,975 acre inches were pumped during replication 5 and minimum of zero acre inches during replications 6 and 15.

Table 13. Summary of Total Acre Inches Pumped, Net Farm Income and Net Worth for Resource Situation 2 With a Quantity Restriction on Water Use[a]

	Year																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Total Acre Inches Pumped																				
Mean	5472	5560	5679	5599	5636	5643	5699	5696	5642	5597	5638	5691	5537	5673	5590	5627	5637	5545	5659	5665
Std. Dev.	697	397	54	267	536	154	17	19	166	309	192	15	467	52	293	232	216	607	147	141
Maximum	5730	5722	5722	5722	6639	5722	5722	5722	5722	5722	5722	5722	5716	5716	5692	5715	5722	5722	5723	5722
Minimum	3008	4297	5490	4770	3911	5130	5673	5672	5051	4545	4950	5677	4005	5490	4567	4791	4860	3352	5230	5160
Range	2722	1425	232	952	2738	592	49	50	671	1177	772	45	1711	226	1125	924	462	2370	593	562
Net Farm Income																				
Mean	9576	10791	12367	12200	13440	13787	12984	11561	12885	15079	13497	12311	13352	12874	14451	13427	15762	14816	13429	15632
Std. Dev.	4528	6180	4362	5303	5094	6768	5299	5558	5439	5879	6316	4536	6467	5293	4614	4608	4347	5963	6252	3761
Maximum	16468	24380	21365	22255	24923	24587	23574	20881	23940	25220	25314	20194	26891	20889	23891	20475	24905	25061	22218	22632
Minimum	2950	2056	5955	4676	6450	2323	952	3046	5108	6979	4019	7922	2797	4388	8898	6207	8768	757	3955	10572
Range	13518	22324	15410	17579	18473	22264	22622	17835	18832	18241	21295	12272	24094	16501	14993	14268	16137	24304	18263	12060
Coef. of Var.	0.47	0.57	0.35	0.43	0.38	0.49	0.41	0.48	0.42	0.39	0.47	0.37	0.48	0.41	0.32	0.34	0.28	0.40	0.47	0.24
Net Worth																				
Mean	122422	124338	127707	130959	135085	139384	143197	145803	149548	155118	159566	163292	167938	172412	178031	184999	189558	195606	200897	208230
Std. Dev.	3645	6531	8685	11109	12248	16215	19241	21047	21922	24186	26861	29457	30820	33197	34851	37023	38707	41322	43073	44598
Maximum	127874	139167	146925	158560	163443	171039	173098	173151	177219	184875	186774	193090	206940	210573	222820	231064	240426	250272	263798	273540
Minimum	116961	113611	114148	116986	121293	116013	114903	111556	114290	114120	112121	111747	115898	115480	119606	117778	123374	121680	120504	125291
Range	10913	25556	32677	41574	42150	55026	58195	61595	62929	70755	74653	81343	91042	95093	103214	113286	117052	128592	143294	148249

[a]The values in this table are based on 15 replications. The values for each replication are reported by Mapp [61, pp. 181, 183, 185].

Remaining saturated thickness of the underground aquifer at the end of the 20-year simulation run ranges from 36.08 to 41.57 feet, averaging 38.37 feet. With a beginning saturated thickness of 100 feet, an average remaining saturated thickness of 38.37 feet indicates a 61.33-foot decline in the water table. Over the 20-year period, the rate of decline averages 3.07 feet per year. Thus, even with a quantity limitation of 1.5 acre feet per acre of water rights, significant reductions is saturated thickness occur over a 20-year period. The distribution of water withdrawals differs from the unrestricted pumping situation. With the quantity limitation, less water is withdrawn in early years and more in late years of the 20-year simulation, but the resulting decline in saturated thickness is very similar in magnitude for both situations.

Net Farm Income

The effect on net farm income for representative farms in Resource Situation 1 of a limit on the quantity of irrigation water pumped per year also is illustrated in Table 12. The mean, standard deviation, maximum, minimum and range in net farm income are shown for each year of the 20-year run.

Mean values of net farm income generally reflect the developement and expansion of irrigation facilities over time, as well as the impact of the declining water level on system pumping capacity, pumping costs per acre inch and the transition from irrigated to dryland production. Mean net farm income increases from $8,791 in year 1 to $11,250 in year 3. The impact of increased pumping capacity caused by the addition of well 2 is reflected in year 3 net farm income. The maximum value of mean net farm income is $12,270 and occurs in year 5. There are at least two plausible explanations tor the maximum occurring in year 5. (1) With the quantity restriction on water pumping in effect, the excess pumping capacity created by addition of well 2 in year 3 is not depleted as rapidly as under the unrestricted alternative. Thus, adequate water may be applied with precise timing to insure good to excellent irrigated crop yields. (2) Excellent crop yields over the initial years are translated into substantial wheat and feed grain payments which, of course, contribute directly to net farm income.

Mean net farm income declines from year 5 through year 8, increases during years 9 and 10, reflecting additional irrigation expansion to a three-well system. In most years the third well is added after crop year 9 and mean net farm income in year 10 is $11,899. Mean net farm income declines dramatically to $7,815 in year 11 and to $5,613 in year 12, but stablizes for years 13 through 16. Year 17 mean net farm income of $7,581, contradicts the trend due primarily to favorable random weather events leading to increased crop yields despite declining well yields. Mean net farm income in years 19 and 20 is $1,253 and $2,447, respectively.

Standard deviation of net farm income has a general upward trend through time. Relative variability, as measured by the coefficient of variation, is virtually stable for years 1 through 10, ranging from a low of 0.44 in year 3 to a high of 0.57 in year 2. The coefficient of variation increases from 0.52 in year 10 to 1.18 in year 13 and remains in the 0.95 to 0.97 interval before declining to 0.67 in year 17. Thereafter, the coefficient rises rapidly to 1.37 in year 18 and 5.36 in year 19 before declining to 2.62 in year 20. The large coefficient of variation in year 19 is attributable to a combination of factors including (1) continued irrigation of acres which were marginally profitable during year 18, and (2) insufficient water to offset lack of natural rainfall during the growing season. The mean net farm income for year 19 is only $1,253, while standard deviation is $6,719. The replications during which the operator continues to irrigate with insufficient pumping capacity results in negative net farm incomes and the resulting increase in magnitude of the coefficient of variation.

In general, variability of net farm income with a quantity limitation exceeds variability of net farm income under conditions of unrestricted pumping. From years 17 through 20, variability of net farm income, as measured by the coefficient of variation, were quite similar for both the unrestricted water-use alternatives.

Net Worth

Restricting water use to 5,670 acre inches per year has a definite and significant impact on the representative firm's net worth over the 20-year simulation run. Net worth of the firm follows a sigmoid pattern over the 20-year interval, first increasing at an increasing rate, then at a decreasing rate and finally decreasing absolutely.

Table 12 includes a summary of net worth figures generated from 15 replications of a 20-year simulation of the quantity limitation. Mean, standard deviation, maximum, minimum and range of net worth are shown for each year. Mean net worth increases from $120,575 at the end of year 1 to $142,714 in year 11. Thereafter, net worth decreases steadily to $115,617 in year 20. It should be noted that ending mean net worth in year 20 is less than mean net worth after year 1 of the simulation sequence. If farm managers operating in the poor water resource situation react to the quantity limitation in the manner assumed in this model, indications are that depletion of the water supply coupled with gradual conversion toward dryland farming in years 11 through 20 results in absolute reductions in net worth within a 20-year period.

Standard deviation of net worth increases steadily over the 20-year simulation period. The transition is from a mean and standard deviation of $120,575 and $3,825, respectively, in year 1 to a mean and standard deviation of $115,617 and $61,094, respectively, in year 20. In terms of relative variability, this transition corresponds to an increase in the coefficient of variation from 0.03 to 0.54. The maximum and minimum values of net worth generated by the Farm Firm Subset occur in years 19 and 20, respectively. Maximum net worth equals $206,441 and minimum net worth equals $2,198. It might be argued that the rational farm operator would quit farming before reducing net worth to such a low level. The overall implications of simulating a quantity restriction on pumping by individual firms appear clear. Over time profitability and net worth of the firm increase until declining water supplies and rising water costs force the conversion toward dryland farming. From that point on, profitability and net worth decline. It is not unrealistic for net worth at the end of 20 years to be less than it was at the beginning of the period. It is likely that ending net worth is significantly lower than for the irrigator who is not restricted in his pumping over time.

Effects of a Quantity Restriction on Resource Situation 2

The quantity restriction limits the individual irrigator to pumping 1.5 acre feet per acre of water rights. For the representative farm firm with 315 irrigated acres, the limitation is 5,670 acre inches per crop year, the same quantity limit used in Resource Situation 1. It is assumed the irrigator, rather than pump water with abandon in every critical irrigation period, also follows the same decision rules regarding use of his limited water supply as the irrigator in Resource Situation 1.

Acre Inches Pumped

The effect of a quantity restriction on acre inches pumped per crop year is reflected in Table 13. The table presents the mean, standard deviation, maximum, minimum, and range of total acre inches pumped per year over the 20-year simulated time period.

Mean values showed little variability, as expected, ranging from a minimum of 5,472 acre inches in year 1 to a maximum of 5,699 acre inches in year 7. Individual yearly observations show considerably more variation. The maximum number of acre inches pumped during any year is 5,730 in year 1. The minimum number of acre inches pumped, 3,008, also occurred during year 1, resulting in a maximum range of 2,722 acre inches during year 1.

Saturated thickness remaining at the end of the 20-year simulation runs varies from a minimum of 250.82 feet to a maximum of 254.26 feet. Mean saturated thickness after 20 years under the quantity restriction is 251.81 feet. Assuming a beginning saturated thickness of 325 feet, this represents an average decline in saturated thickness of 73.19 feet or 3.66 feet per year. This rate of decline under the quantity restriction compares to the 4.50 feet per year decline for the unrestricted pumping alternative. The implications of various water-use rates for different regulatory alternatives is discussed in detail in a subsequent section.

Net Farm Income

The mean, standard deviation, coefficient of variation, maximum, minimum and range of net farm income were computed for each crop year and are also shown in Table 13. Net farm income under quantity restriction follows essentially the same pattern as under the unrestricted water-use alternative except that the level of income is considerably lower under the quantity restriction. Mean values of net farm income increase from the minimum level of $9,576 for year 1 to $15,632 in year 20, however, the highest mean net farm income is $15,762 in year 17. A major proportion of the increase results during the first five years and is attributable to increased yields leading to increased government payments. From year 1 to year 5, net farm income increases from $9,576 to $13,440, or by $3,864. During the same period, government payments, composed of wheat certificate and feed grain payments, increase from $7,610 to $11, 406, or $3,796. After year 5, total government payments, which are computed on the basis of five-year moving

Table 12. Summary of Total Acre Inches Pumped, Net Farm Income and Net Worth for Resource Situation 1 With a Quantity Restriction on Water Use[a]

	Year																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Total Acre Inches Pumped																				
Mean	5387	5466	5704	5661	5599	5656	5687	5674	5566	5339	5601	5644	5244	4817	3990	3561	3116	2559	2489	1791
Std. Dev.	768	450	26	121	391	159	13	79	305	534	288	114	615	817	638	720	624	634	393	925
Maximum	5710	5708	5741	5739	5728	5730	5714	5716	5715	5694	5717	5712	5709	5701	5097	4442	4000	3621	3173	2975
Minimum	2851	4227	5636	5257	4188	5084	5673	5394	4600	4024	4583	5295	3623	2970	2939	1802	1988	1157	1796	0
Range	2859	1481	105	482	1540	646	41	322	1115	1570	1134	417	2086	2731	2158	2640	2012	2464	1377	2975
Net Farm Income																				
Mean	8791	9715	11250	11131	12270	12707	11417	9913	10234	11899	7815	5613	6204	5621	5586	5335	7581	4591	1253	2447
Std. Dev.	4703	5548	4941	5815	5412	6926	5519	5099	5650	6164	6780	5557	7314	5567	5329	5489	5056	6295	6719	6400
Maximum	15567	22923	21290	22023	23559	23952	21864	18723	20746	22296	20585	16739	20396	13841	15133	12322	15020	12777	13187	13910
Minimum	2280	2102	3186	2476	4518	1056	-1160	2614	2398	2153	-3292	-2921	-7607	-2724	-2909	-4262	-132	-11727	-10800	-10007
Range	13287	20821	18104	19547	19041	22896	23024	16109	18348	20143	23877	19660	28003	16565	18042	16584	15152	24504	23987	23917
Coef. of Var.	0.53	0.57	0.44	0.52	0.44	0.55	0.48	0.51	0.55	0.52	0.86	0.99	1.18	0.99	0.95	0.97	0.67	1.37	5.36	2.62
Net Worth																				
Mean	120575	121620	123890	126086	129165	132506	134916	136115	137592	140430	142714	140513	138615	136320	133937	131294	130695	127367	120903	115617
Std. Dev.	3825	6043	8455	11314	12275	15483	19805	22033	23178	25921	29252	33201	35892	39565	42733	46457	49403	53403	57903	61904
Maximum	126009	135524	142473	153603	156761	163285	164465	165447	167270	172615	174443	176468	168443	186491	190856	192574	197294	201406	206441	205332
Minimum	115128	112423	112779	109463	114607	111754	104866	99873	99156	98546	90879	82845	79670	69812	61469	52776	49074	29851	15686	2198
Range	10881	23101	29694	44140	42154	51531	59599	65574	68114	74069	83564	93623	106773	116679	129387	139798	148220	171555	190755	203134

[a] The values in this table are based on 15 replications. The values for each replication are reported by Mapp [61, pp. 141, 143, 147].

averages for the individual crops concerned, stabilize in the $10,700 to $11,500 range. Net farm income continues to rise, in general, but with considerable variability.

Relative variability, of net farm income, as measured by the coefficient of variation, fluctuates from year to year. The maximum value is 0.57 in year 2 and the minimum value is 0.24 in year 20. Variability of net farm income is related to yield variability. The quantity restriction results in failure to fully irrigate grain sorghum during boot-heading and grain-filling stages of crop development and failure to preplant irrigate all irrigated wheat acreages. During years in which full irrigation applications cannot be completed, final crop yield is more dependent upon highly variable natural rainfall. Thus, restricting the quantity pumped to 5,670 acre inches per year reduces crop yield, increases yield variability and, as a result, increases variability of net farm income.

Net Worth

The final portion of Table 13 summarizes the effects of a quantity restriction on net worth for representative farms in Resource Situation 2. The mean, standard deviation, maximum, minimum and range of net worth for each year are given.

Net worth increases continuously from year 1 through year 20. Beginning net worth at the end of year 1 is $122,422. Ending net worth is $208,230. Between the two points, mean values of net worth increase approximately linearly. The maximum value of net worth generated during any simulated year ($273,540) occurs as expected, during year 20. The minimum net worth value for any year ($113,611) is generated in year 2.

Effects of a Graduated Tax on Resource Situation 1

The third institutional alternative considered is the imposition of a per unit tax on each acre inch of water pumped above the quantity limitation. The irrigator is assumed to follow the same set of decision rules as specified for irrigators facing a quantity restriction, with one exception. The irrigator is allowed to pump as many acre inches above the limitation as he desires so long as he pays a graduated tax of $0.50 for each acre inch pumped above the limit. An economic decision rule is followed by irrigators in deciding whether or not to apply water above the limit. The irrigator evaluates the potential yield reduction which will occur, projecting present moisture conditions, if he does not irrigate. The value of the potential loss for a given crop block is compared with the cost of an additional irrigation, plus added harvesting and hauling costs. If the value of potential yield reduction exceeds the cost of an additional irrigation, the application is made. The decision rules followed are discussed above.

Acre Inches Pumped

Table 14 summarizes the effects of a graduated tax per unit above the quantity limit on total acre inches pumped during 15 replications of each of 20 crop years. The mean, standard deviation, maximum, minimum and range of acre inches pumped have been computed for each year of the simulation analysis.

Mean values of total acre inches pumped per year reflect the expansion and development of irrigation facilities on the farm firm representing Resource Situation 1. That is, the highest number of acre inches pumped occurs during year 3, reflecting the excess pumping capacity created by addition of a second irrigation well. Mean acre inches pumped fluctuates between 6,040 and 6,144 acre inches to year 7 and then declines until the addition of well 3, which usually occurs at the end of crop year 10. The addition of well 3 results in a pumping increase during year 11. From year 12 through year 20, mean acre inches pumped declines steadily, reaching 1,447 acre inches during year 20.

Simulation of the graduated tax results in complete conversion to dryland production during five of the fifteen replications of the 20-year simulation run. In four of the five replications the final transition comes in year 20. In one replication both years 19 and 20 are simulated with complete dryland production. This pattern of conversion to dryland production exhibits the same timing characteristics as exemplified in the unrestricted simulation analysis. The quantity of water pumped under taxation is less than under unrestricted pumping, however, the addition of a per unit tax on each unit above the quantity limitation results in a similar timing of conversion to dryland production.

The maximum number of acre inches pumped during any replication is 7,216 during year 4. The minimum, of course, is zero and occurred during both years 19 and 20. The maximum range within a single year of 5,417 acre inches occurs during year 4, when

Table 14. Summary of Total Acre Inches Pumped, Net Farm Income and Net Worth for Resource Situation 1 with a Graduated Tax Per Unit Pumped Above the Quantity Limit. [a]

	Year																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Total Acre Inches Pumped																				
Mean	5549	5429	6371	6045	6144	6040	6115	5878	5514	5580	5954	5659	4836	4266	3533	3274	2854	2508	2483	1447
Std. Dev.	929	451	500	1408	666	463	223	397	472	639	488	573	717	741	497	673	486	522	1113	1085
Maximum	6072	5842	7118	7216	7109	6732	6426	6312	6111	6604	6488	6373	5652	5300	4364	4263	3790	3271	5705	2529
Minimum	2722	4226	5500	1799	4530	5094	5519	5085	4396	4390	4572	4481	3315	2867	2791	1894	2066	1087	0	0
Range	3350	1616	1618	5417	2579	1638	907	1227	1715	2214	1916	1892	2337	2433	1573	2369	1724	2184	5705	2529
Net Farm Income																				
Mean	9473	10461	13595	14042	14966	15346	14333	12995	12842	13368	10477	8018	8865	8288	9270	8065	9956	6944	3867	5056
Std. Dev.	4499	5327	3918	4953	4436	6305	4891	4553	5317	5902	5910	4583	7117	5038	4548	4257	2491	5799	5695	5667
Maximum	16394	23014	21994	23259	24074	25073	23766	20683	22930	23625	21125	16670	23583	16016	20608	12898	17195	14356	11529	17229
Minimum	3493	3246	7280	7179	8610	4556	3115	6225	4105	5560	510	1489	-2778	1463	3036	-275	4764	-6463	-4418	-3920
Range	12901	19768	14714	16080	15464	20517	20651	14448	18825	18065	20615	15181	26361	14553	17572	13173	12431	20819	15942	21149
Coef. of Var.	0.47	0.51	0.29	0.35	0.30	0.41	0.34	0.35	0.41	0.44	0.56	0.57	0.80	0.61	0.49	0.53	0.43	0.84	1.47	1.12
Net Worth																				
Mean	121150	122833	127009	131559	136827	142331	147196	150995	154741	160349	163903	164060	164886	164234	16641	166762	168633	167714	164086	161676
Std. Dev.	3607	5653	7536	9847	10268	13848	16486	18075	18847	20570	24426	27310	29337	34823	33874	36645	38763	41459	44808	48017
Maximum	126622	136305	144574	156630	161736	169614	172764	176163	179803	187048	189066	193850	206338	207107	214434	218592	224886	228764	233555	235767
Minimum	116287	114135	11647	118636	125491	123708	121722	120623	122730	125214	118202	113229	112449	106347	106036	98261	97124	89890	77978	66865
Range	10335	22170	27927	37994	36245	45906	51042	55540	57073	61834	70864	80621	93889	101360	108398	120331	127762	138874	155577	268902

[a] The values in this table are based on 15 replications. The values for each replication are reported by Mapp [61, pp. 150, 153, 155].

a maximum of 7,216 acre inches and a minimum of 1,799 acre inches are pumped.

The range in remaining saturated thickness at the end of the 20-year simulation period is from 34.67 to 40.97 feet, averaging 37.72 feet. Translating this into feet decline in saturated thickness results in an average foot-decline of 62.28 feet over the 20-year period, or an average of 3.11 acre feet per year. Of the total volume of water underlying the representative farm, assuming a beginning saturated thickness of 100 feet, only about 38 percent remains at the end of 20 years under the graudated tax alternative.

Net Farm Income

The effects on net farm income of a graduated tax on each acre inch of irrigation water pumped above the quantity limitation also are illustrated in Table 14. The mean, standard deviation, maximum, minimum and range of net farm income have been computed for each year of the 20-year simulation run.

Mean values of net farm income increase steadily from $9,473 in year 1 to $15,346 in year 6. This dramatic rise may be attributed to several interrelated factors. First, expansion of irrigation facilities by the addition of well 2 increases pumping capacity significantly. Second, the additional pumping capacity insures proper timing for the very profitable irrigations of grain sorghum and wheat in irrigation periods 4 and 5. Higher wheat and grain sorghum yields lead not only to increased net returns per acre, but to higher government payments for the farm operator. Mean net farm income declines during years 7, 8 and 9, but increases to $13,368 in year 10 with the addition of irrigation well 3. Thereafter, mean net farm income declines steadily except for individual yearly increases due to favorable soil moisture and atmospheric stress conditions in years 15 and 17.

The maximum value of net farm income generated in any year is $25,073 in year 6. The minimum of -$6,463 occurred in year 18. The greatest range occurs during year 13 with the difference being $26,361.

Variability, as measured by the standard deviation, does not follow a definite trend. Generally, it rises when mean net farm income rises and declines as net farm income declines, remaining between 0.29 and 0.61 for the initial seventeen years. Coefficients of variation for years 18, 19 and 20 are 0.84, 1.47 and 1.12, respectively. Stability of net farm income is greater under the graduated tax than under either the unrestricted or quantity restriction alternatives.

Net Worth

Table 14 summarizes the effects on net worth for representative firms in Resource Situaion 1 of a graduated tax on each acre inch of water pumped above the quantity limitation. The mean, standard deviation, maximum, minimum and range of net worth have been computed across the 15 replications of each year of the simulation run.

Net worth of the representative farm firm increases steadily from year 1 through year 13, dips slightly in year 14 and increases during years 15, 16 and 17, before declining in years 18, 19 and 20. The maximum mean value of $168,633 occurs in year 17. Variability of net worth increases steadily also from 0.03 in 1 to 0.30 in year 20. Maximum and minimum individual values of net worth both occur during year 20. The maximum net worth of $235,767 is generated during replication 5, while the minimum value of net worth of $66,865 is generated in replication 6. Mean value of ending net worth in year 20 is $161,676.

Effects of a Graduated Tax on Resource Situation 2

The effects of imposing a tax of $0.50 per acre inch on each acre inch pumped above the 5,670 acre inch limit are discussed below. The decision rules followed in allocating water during the growing season are the same as those used under Resource Situation 1.

Acre Inches Pumped

Table 15 presents a summary of total acre inches pumped under the graduated tax alternative for 15 replications of a 20-year simulation of Resource Situation 2. The mean, standard deviation, maximum, minimum and range of acre inches pumped are shown for each of the 20 years.

Mean values of total acre inches pumped range from a low of 5,875 in year 1 to a high of 6,274 in year 12. Fluctuations between these extremes follow no definite pattern. Variation in acre inches

Table 15. Summary of Total Acre Inches Pumped, Net Farm Income and Net Worth for Resource Situation 2 With a Graduated Tax Per Unit Pumped Above the Quantity Limit[a]

	Year																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Total Acre Inches Pumped																				
Mean	5875	6010	6035	6070	5931	6000	6249	6157	6107	5960	6131	6274	6173	6209	6073	6209	6161	6032	6099	6130
Std. Dev.	1046	668	391	651	696	488	225	458	576	645	451	343	765	460	559	436	410	806	511	416
Maximum	6795	6750	6495	6780	6735	6735	6660	6735	6735	6570	6735	6795	6735	6735	6645	6645	6645	6645	6795	6645
Minimum	2722	4297	5265	4695	3911	5130	5850	5402	4699	4320	4950	5535	3915	5310	4477	4791	4860	3352	4950	5160
Range	4073	2453	1230	2085	2824	1605	810	1333	2036	2250	1785	1260	2860	1425	2168	1854	1785	3293	1845	1485
Net Farm Income																				
Mean	10866	12380	14314	14604	16383	16790	61651	14990	16298	18456	16871	15739	16798	16501	18036	17216	19572	18631	16921	19020
Std. Dev.	4294	5722	3917	4933	4557	5966	4582	4761	5225	4984	5215	3985	6265	4698	4269	3871	3945	4923	5827	3730
Maximum	17467	24866	22849	23613	26549	26348	24667	23944	26176	26617	25974	22849	31541	23656	27520	22035	26908	26596	24582	24621
Minimum	4629	4428	8132	7479	10173	6705	5236	8493	8161	11051	9148	11093	7631	7678	11608	10126	12841	7567	7869	12329
Range	12838	20438	14717	16134	16376	19643	19431	15451	18015	15566	16826	11756	23910	15978	15912	11909	14067	19029	16713	12292
Coef. of Var.	0.40	0.46	0.27	0.34	0.28	0.36	0.28	0.32	0.32	0.27	0.31	0.25	0.37	0.28	0.24	0.22	0.20	0.26	0.34	0.20
Net Worth																				
Mean	123468	126713	131705	136975	143491	150247	156733	162247	168920	177506	185138	191906	200203	208430	217774	226535	237395	247674	257181	268714
Std. Dev.	3416	5913	7635	9573	10055	13322	15712	16875	17470	19297	21553	24467	24636	36286	27381	28991	29756	31502	32494	33184
Maximum	128627	139948	148184	160773	166971	175788	180248	184081	190531	200388	205715	217482	233771	241188	255038	266398	280915	294494	310292	323366
Minimum	118464	116832	119772	124094	132114	131737	132641	133200	138895	144216	144810	148885	157447	162519	171583	176140	186929	186838	195235	205603
Range	10163	23116	23412	36679	34857	44051	47607	50881	51636	56172	60905	68597	76324	78669	83455	90258	93986	107657	114967	117763

[a] The values in this table are based on 15 replications. The values for each replication are reported by Mapp [61, pp. 188, 190, 192].

pumped per year exceed that of the quantity restriction, but are not as great as under unrestricted pumping. The maximum number of acres inches pumped is 6,795 and occurs during three different years — years 1, 12 and 19. The minimum number of acre inches pumped is 2,722 in year 1, thus the maximum range in acre inches pumped also occurs in year 1.

Saturated thickness at the end of the 20-year simulation runs ranges from 242.88 to 249.19 feet, averaging 245.61 feet. Assuming a beginning saturated thickness of 325 feet, the average decline in saturated thickness is 79.39 feet, or about 3.97 feet per year. This rate of decline compares with 4.50 feet per year for the unrestricted alternative and 3.66 feet per year for the quantity limitation alternative.

Net Farm Income

The middle section of Table 15 presents the mean, standard deviation, maximum, minimum, range and coefficient of variation of net farm income under the graduated tax alternative for Resource Situation 2. Mean values of net farm income under the graduated tax alternative increase generally over the 20-year period, though not without yearly fluctuations. The lowest mean net farm income is $10,866 in year 1 and the highest is $19,572 in year 17. Mean net farm income in year 20 is $19,020. A rapid rise in mean net farm income occurs from year 1 ($10,866) to year 6 ($16,790), largely because of a rapid increase in government payments (from $8,217 in year 1 to $13,296 in year 5). Government payments are relatively stable (between $12,900 and $13,300 per year) after year 5, but the mean values of net farm income continue to rise. Relative variability as measured by the coefficients of variation, is greatest in years 1 and 2 (0.40 and 0.46, respectively) and declines as a larger portion of net farm income is received from government payments. It remains in the 0.20 to 0.37 range after year 5.

The maximum value of net farm income generated is $31,541 in year 13, while the minimum value is $4,428 in year 2. The maximum range in net farm income, $23,910, occurs in year 13.

Net Worth

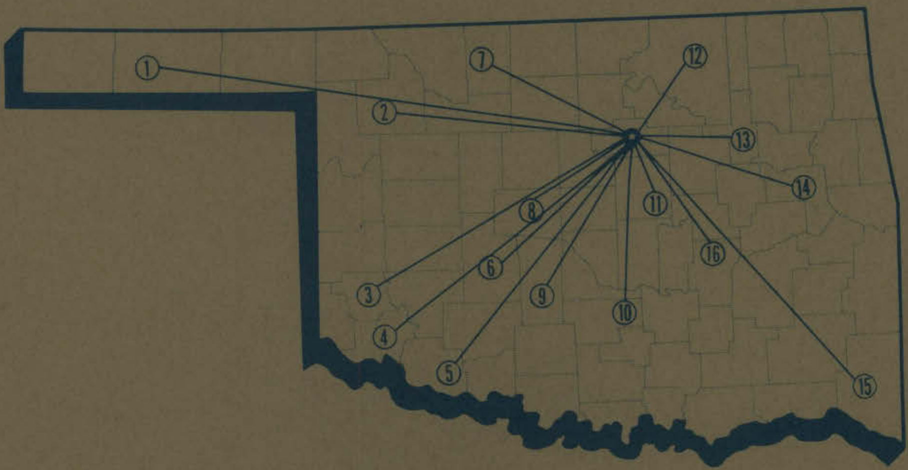
The lower portion of Table 15 presents a summary of net worth resulting from 15 replications of a 20-year simulation of Resource Situation 2 under the graduated tax alternative. Mean values of net worth increase steadily from $123,468 in year 1 to $268,714 in year 20. The increase is approximately linear. The combination of increased government payments during the initial five years, retirement of chattle and real estate debts over the next ten years and accumulation of excess cash reserves combine to increase net worth at a relatively constant rate over time.

The maximum value of net worth generated by the fifteen replications is $323,366 in year 20. The minimum value of $116,832 occurs in year 2. The maximum range in net worth (of $117,763) occurs in year 20.

OKLAHOMA

Agricultural Experiment Station

System Covers the State



Main Station — *Stillwater, Perkins and Lake Carl Blackwell*

1. **Panhandle Research Station — *Goodwell***
2. **Southern Great Plains Field Station — *Woodward***
3. **Sandyland Research Station — *Mangum***
4. **Irrigation Research Station — *Altus***
5. **Southwest Agronomy Research Station — *Tipton***
6. **Caddo Research Station — *Ft. Cobb***
7. **North Central Research Station — *Lahoma***
8. **Ft. Reno Livestock Research Station — *El Reno***
9. **South Central Research Station — *Chickasha***
10. **Agronomy Research Station — *Stratford***
11. **Pecan Research Station — *Sparks***
12. **Veterinary Research Station — *Pawhuska***
13. **Vegetable Research Station — *Bixby***
14. **Eastern Pasture Research Station — *Muskogee***
15. **Kiamichi Field Station — *Idabel***
16. **Sarkeys Research and Demonstration Project—*Lamar***

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