A RECURSIVE PROGRAMMING ANALYSIS OF WATER CONSERVATION IN ARIZONA AGRICULTURE: A STUDY OF THE PHOENIX ACTIVE MANAGEMENT AREA

by

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and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

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Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copy of the dissertation to the Graduate College.

I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

James C. Wade
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November 17, 1983
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SIGNED: Wally Kent Wyman

This study is dedicated to my wife, Janey, whose love, encouragement, and support has made this work and life worthwhile.

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ABSTRACT

Arizona agriculture faces many changes in the near future. One of the most imminent changes will come from the enactment of the 1980 Arizona Groundwater Management Act. The 1980 AGWMA is designed ultimately to curtail the use of groundwater in Arizona. Agriculture will be affected since this sector used approximately 87 percent of all water in the State in 1980.

This study reports on the possible effects that a proposed pump tax and water duty policy would have on agriculture within the Phoenix Active Management Area. The PAMA is one of four such areas in the State that have been identified as needing groundwater use management.

The results of this study indicate that the proposed water duty is more effective in curbing groundwater use than the proposed pump tax. Investment in more water application efficient irrigation technologies is also important in this study. However, substantial amounts of capital investment funds will be needed to begin this investment.

CHAPTER 1

INTRODUCTION

Arizona agriculture relies on available water supplies from groundwater, surface water, and treated sewage effluent to irrigate crops. Groundwater supplies are the most important source of irrigation water for agriculture. Total state-wide water use is estimated to have been 8.6 million acre-feet in 1980 (Arizona Department of Water Resources, 1983). Agriculture used approximately 87 percent of the 8.6 million acre-feet, or an estimated 7.48 million acre-feet of surface water diverted to farms, pumped groundwater, and treated sewage effluent. While the Arizona Department of Water Resources does not have current estimates of the percentage of total irrigation water from groundwater or surface water sources, estimates have been made which indicate that of the 8.6 million acre-feet used in the state, approximately 6.1 million acre-feet was groundwater and 2.5 million acre-feet was surface water and effluent. In 1980, therefore, approximately 71 percent of the 1980 state-wide water use was from groundwater and 29 percent was from surface water and effluent. The importance of groundwater supplies to Arizona agriculture also has been noted previously by other authors who pointed out that ". . . more water is provided annually by pumps from underground than from surface sources" (Kelso, et al., 1973, p. 22).

Up to the present time, available water supplies have been used extensively in Arizona by agriculture and other sectors of the state's economy. Extensive use of groundwater has resulted in an estimated groundwater overdraft of 2.1 million acre-feet in 1970 (Arizona Statistical Review, 1979). The overdraft continues.

As a consequence of the apparent over-use of groundwater supplies, concern has increased among Arizona's politicians, as well as the general citizenry over the use of the state's groundwater supplies. Lawmakers within the state recently passed legislation aimed at curbing the excessive use of groundwater supplies in Arizona. The 1980 Arizona Groundwater Management Act, or 1980 AGWMA, incorporates policies whose intent is to manage and ultimately to decrease groundwater use in Arizona.

While the goal of the 1980 AGWMA is to regulate groundwater use in Arizona, enactment of the legislation will also bring about changes in Arizona agriculture: changes will occur, to varying degrees, in groundwater use, net revenues, crop mixes, energy use, and irrigation technologies depending upon the policies enacted to regulate groundwater use. The 1980 AGWMA has proposed the use of a pump tax and/or a water duty to reduce groundwater use in Arizona's irrigated agriculture. The objective of the research presented in this study is to evaluate the economic impact of alternative policies for reducing groundwater use in one of Arizona's four groundwater management areas.

Purpose of This Study

The purpose of this study is to examine expected changes in net revenues, groundwater use, energy use, crop mixes, and irrigation technologies resulting from the implementation of policies of the 1980 AGWMA in the PAMA study area described below. The study will examine the pump tax and water duty policies which have been designed to regulate the use of and to consume groundwater.

The results of this study should produce information applicable to policymakers. One possible use of the results would be to determine the best mix of irrigated crops and irrigation technologies for use in the PAMA given the provisions of the 1980 AGWMA. A related result would be to determine the total amount of investment required to achieve this mix of technologies. Such results could provide the Arizona Department of Water Resources and Federal agencies such as the Soil Conservation Service, or SCS, with investment targets that could result in achieving the best mix of irrigation technologies.

The study also examines the relative effectiveness of two groundwater management policies in achieving the goal of the 1980 AGWMA relating to groundwater use in agriculture. Officials of the Arizona Department of Water Resources and other water management agencies could benefit from having an estimate of the possible economic impacts of proposed policies. How effective are the pump tax and water duty in decreasing groundwater use? How might profits react if the water duty is made more severe through time? Finally, farmers may use the results to gain insight into the types of crops, crop mixes, and technologies which could maximize net revenues in their own operations and their respective districts.

The specific objectives of this study are to:

1. Project and compare changes in water use in the Phoenix Active Management Area when the pump tax and water duty of the 1980 AGWMA are implemented as opposed to when neither alternative is employed,
2. Project and compare changes in net revenues in each irrigation district and the region when the pump tax and water duty policies of the 1980 AGWMA are implemented and when these policies are not employed in the Phoenix Active Management Area,
3. Project changes in crop mixes and cropped acres in the Phoenix Active Management Area when the pump tax and water duty policies of the 1980 AGWMA are implemented as opposed to when neither policy is utilized,
4. Project changes in acreage irrigated by alternative irrigation technologies in the Phoenix Active Management Area when the pump tax and water duty policies of the 1980 AGWMA are employed and when neither policy is used,
5. Project changes in energy use in the Phoenix Active Management Area when the pump tax and water duty policies of the 1980 AGWMA are implemented and when neither policy is used.

Background to the Arizona Groundwater Management Act

Historically, legislation pertaining to water in Arizona has dealt with the question of who has rights to the water itself, but not necessarily with the question of how the water could be used or how much water could be used. Only recently, in 1968, did the intent of these water related resolutions begin to focus on how existing groundwater supplies could be developed by claimants to these supplies. The 1968 legislation sought to moderate the depletion of groundwater supplies in the state through the establishment of critical groundwater areas or CGAs.

The 1980 AGWMA went a step beyond previous legislation as the first act of its kind to attempt to regulate the amounts of groundwater supplies used in Arizona. The management and regulation of withdrawal, use, conservation, and conveyance of rights to the use of groundwater supplies is the stated intent of the 1980 AGWMA. The ultimate goal of the 1980 AGWMA is a "safe yield" (a balance between withdrawals and natural and artificial recharge of groundwater supplies) by January 1, 2025. More correctly, the management goal of the 1980 AGWMA is a "safe yield" in the Tucson, Phoenix, and Prescott Active Management Areas. The goal in the Pinal Active Management Area is preserving existing agriculture for as long as is feasible, consistent with the need to preserve water supplies for non-irrigation uses (Summary, Groundwater Management Act, Arizona Groundwater Study Commission Staff, June, 1980, p. 28).

Available and affordable water supplies have always been a constraint on the expansion of agriculture in Arizona. The absence of an affordable and dependable water supply has determined the amount of arable land developed for irrigation (Arizona State Water Plan, Phase I). With the passage of the act, Arizona agriculture entered a new era. As a result, Arizona agriculture will undergo numerous changes with the enactment of the 1980 AGWMA and its attendant policies.

The Policies of the 1980 AGWMA

There are many articles, policies, and provisions associated with the 1980 AGWMA. In this study, two policies are considered which may bring about substantial changes in Arizona agriculture. The first policy is a pump tax which raises the cost of groundwater supplies to individual irrigated farms, and the second policy establishes the maximum quantity of groundwater which an irrigation user may pump during a given time period, called a "water duty."

The provisions of the 1980 AGWMA are to be administered by the Arizona Department of Water Resources (ADWR) which was established by the Act. The law initially applies to four specific active management areas: the Phoenix, Tucson, Pinal, and Prescott Active Management Areas in Maricopa, Pima, Pinal, and Yavapai Counties, respectively. However, the "Director" of the program can classify other areas as active management areas as needed, to accomplish the goal of the 1980 AGWMA.

Under the 1980 AGWMA the maximum amount of groundwater any commercial irrigation operation can withdraw, given that irrigation grandfathered rights are claimed, is called "the irrigation water duty." The director determines the amount of water that can reasonably be applied per acre of land to satisfy needs of crops and also to promote water conservation. This per acre amount is multiplied by "water duty acres" to determine the maximum amount of groundwater that may be withdrawn. The "water duty acres" are the highest number of acres legally irrigated by a farmer in any one of the five years preceding formation of the AMA (1975-1980 for the four initial AMAs). Thus, the "water duty" is the quantity of water a farmer may pump to irrigate all crops in any given year. However, a farmer cannot expand his agricultural acreage once the 1980 AGWMA is in force. Farmers with access to both surface and groundwater must use the maximum amount of surface water they have access to in satisfying the irrigation water duty. However, the "water duty" does not apply to surface water. Farmers with access only to groundwater may continue pumping groundwater to satisfy the irrigation water duty.

The law provides the option of "banking" allotted groundwater. A farmer can withdraw more groundwater this year, but must curtail use in later years in the same amount. Conversely, farmers can use less in the current year and withdraw the remaining amount of the current irrigation water duty in a later year or years. The use of meters, which will record the amount of water pumped from individual wells, will aid the ADWR in monitoring the banking of groundwater. Meters must be installed on each well by January 1, 1984.

The water duty, which is based on the efficient use and conservation of water, for irrigation users implicitly reflects conservation practices such as improved irrigation management, land leveling, concrete lined ditches, and pumpback systems (Wade and Mezainis, 1983).

The Policies of the AGWMA Used in This Study

The phasing in of the pump tax and water duty policies and other provisions of the AGWMA is tentative at this time. However, a rough time table has been developed for the implementation of the 1980 AGWMA. Gradual reductions in groundwater use are to be attained over a forty-five year time period from 1980 to 2025. The forty-five year management period is divided into five management periods. The Director of the ADWR is to develop a conservation plan for each AMA prior to each period. Users of groundwater will have roughly ten years, from the beginning of each period, to reach the conservation goals set by the Director. In the meantime, the Director may set intermediate conservation goals within a particular management period.

The Pump Tax

The AGWMA provides that $3.00 per acre foot per year charge will be charged for groundwater withdrawals. One dollar will be used for administration and enforcement. The one dollar charge will be matched by the State and is to be levied as soon as possible. The remaining two dollars will be used for the purpose of augmenting the water supply of the AMAs and will be levied in 1988. For the analysis done in this study, it is assumed that the total $3.00 pump tax is levied in the year 1990. The 1980 AGWMA provides for an additional $2.00 per acre foot per year to be levied for the purchase and retirement of grandfathered rights when needed by the 1980 AGWMA. The tentative date chosen, in the 1980 AGWMA, for implementing the $2.00 tax is sometime after 2006. For this study, however, the assumption is made that the additional fee is levied in the year 2000. This is not an unreasonable assumption, given that the AGWMA has yet to have an impact upon groundwater use as of 1983. Therefore, in order to attain the goal of a safe yield by 2025 the additional tax may be implemented earlier than scheduled. Lobbying and the governmental process might delay this additional groundwater withdrawal charge.

The Water Duty

The irrigation water duty is to be determined immediately at the onset of each ten year management period determined by the Director of the 1980 AGWMA. No specific limits on the maximum quantity of groundwater on each acre have been established for the irrigation water duty but a limit of 5 acre feet per acre per year is chosen for this study. This limit is set for the year 1990 for this study.

In 1980, the estimated number of harvested acres of all principal crops in Maricopa County was 502,060 (Arizona Agricultural Statistics, Historical Summary, 1965-1980). The estimated amount of water used for agriculture in Maricopa County was 2.64 million acre-feet in 1980. Dividing the 2.64 million acre-feet of water by the number of harvested acres in 1980 gives 5.25 acre-feet of water used per acre. Therefore, 5 acre-feet per acre for the irrigation water duty in 1990 is a reasonable level for this study. The fact that the 1990 water level used in this study is one quarter acre-foot per acre less than the 1980 figure can be assumed to reflect the emphasis of conservation in the 1980 AGWMA.

The principal idea underlying the irrigation water duty is to achieve conservation ". . . by assuming increasingly sophisticated conservation practices in setting the irrigation water duty" (Summary, Groundwater Management Act, Arizona Groundwater Study Commission Staff, June, 1980, p. 13). In this study, the irrigation water duty becomes the most stringent by the year 2000. In the year 2000, the water duty is 3 acre-feet per acre per year. Three acre-feet per acre has been chosen as representing the average consumptive use for irrigation purposes in the 1980 AGWMA (Summary, Groundwater Management Act, Arizona Groundwater Study Commission Staff, June, 1980, p. 11). However, no specific time period for application of the 3 acre-feet per acre per year limit has been delineated within the 1980 AGWMA. Such a provision would have to come at the discretion of the Director of the ADWR. It seems reasonable to apply the 3 acre-feet per acre limit in the year 2000 in this study. The 3 acre-feet per acre limit is the ultimate limit towards which the AGWMA can move in order to reduce groundwater withdrawals.

Description of the Study Area

The Phoenix Active Management Area, or PAMA, has approximately 3.6 million acres of agricultural and non-agricultural land and the PAMA encompasses most of Maricopa County's agricultural land (Phoenix Active Management Area Office, 1982). Farmers use pumped groundwater, surface water, and treated sewage effluent to irrigate crops.

In 1970, approximately 89 percent of all water withdrawn in the state was used by agriculture. In 1970, approximately 1.7 million acre-feet of an estimated 4.3 million acre-feet of water used by all agriculture in Arizona was used in Maricopa County (Arizona State Water Plan, Alternative Futures, Phase II). The estimated 1.7 million acre-feet of water used in Maricopa County in 1970 compares to an estimated .3 million acre-feet of water used for urban uses in Maricopa County. Roughly 61 percent of the .3 million acre-feet, or 183,000 acre-feet, used by urban uses was depleted or was rendered unavailable for further use (Arizona State Water Plan, Alternative Futures, Phase II). The rate of depletion of water supplies by agriculture was over nine times the rate of depletion by urban uses in 1970 in Maricopa County.

In 1980, the ADWR estimated total water use in Maricopa County to be approximately 3.0 million acre-feet. Of this total, approximately 88 percent, or 2.64 million acre-feet, of the water was used in agriculture. The ADWR has estimated that approximately 68 percent and 32 percent was groundwater and surface water, respectively. Therefore, about 1.8 million acre-feet of groundwater and .8 million acre-feet of surface water was used for agriculture in Maricopa County in 1980.

The PAMA is unique from the other active management areas in several respects. More citrus and vegetable crops are grown in the PAMA than in any other active management area. Estimates of citrus and vegetable acreage within the PAMA were not available at this writing. However, a comparison of 1980 citrus and vegetable acreage for Maricopa County (which encompasses the PAMA) relative to Pinal County (which encompasses the Pinal Active Management Area), Pima County (which encompasses the Tucson Active Management Area) and Yavapai County (which encompasses the Prescott Active Management Area) shows 19,400 acres of vegetables and 17,860 acres of citrus in Maricopa County, 2,000 acres of vegetables in Pinal County with no significant amount of citrus, only 700 acres of vegetables in Pima County with no significant amount of citrus, and only 100 acres of vegetables and no citrus in Yavapai County (Arizona Agricultural Statistics, Historical Summary, 1965-1980).

The PAMA also receives more surface water than the other active management areas. The amount of surface water available in any year depends upon the runoff from the Salt and Verde River watershed. The last three years, 1980-1982, have been exceptional years in terms of runoff in the watershed (Phoenix Active Management Area Office). Some very rough preliminary estimates have been made by the PAMA office regarding surface water use in the PAMA. Nevertheless, these estimates give an indication of the potential magnitudes of surface water use in the PAMA. An estimate of just over .6 million acre-feet of surface water was used by agriculture in the PAMA in 1980 (Phoenix Active Management Office, 1983). Recalling that an estimated .8 million acre-feet of surface water was used in agriculture in Maricopa County in 1980, roughly 75 percent of the surface water used by agriculture in Maricopa County in 1980 evidently occurred in the PAMA. In addition to the .6 million acre-feet of surface water used in the PAMA in 1980, groundwater use in the PAMA was estimated to be just under .9 million acre-feet for a total estimated water use of 1.5 million acre-feet by agriculture in the PAMA in 1980. Of the 2.64 million acre-feet of water used for agriculture in Maricopa County, about 57 percent was used in the PAMA. The Pinal Active Management Area relies primarily on groundwater but also uses surface water in the San Carlos Irrigation and Drainage District and the San Carlos Project Indian Irrigation District (Boster and Martin, 1977, p. 17). The Prescott Active Management Area which includes the Chino Valley Irrigation District uses surface water from Watson Lake and Willow Creek reservoir. The Tucson Active Management Area does not use surface water supplies, but relies totally on pumped groundwater.

The PAMA also encompasses the metropolitan Phoenix area which is the ninth largest city in the country and one of the fastest growing cities in the Sunbelt. The pressure exerted upon the crop acreage base by urban interests in the PAMA is another distinction from the other areas even though some farmland has been converted to urban uses with the expansion of metropolitan Tucson. However, the conversion of agricultural land is greater in the PAMA than in other AMAs. Projections of annual average agricultural land conversion range from 1,577 acres (Arizona Department of Water Resources) to 1,866 acres (Kelso, et al., 1973). The Arizona Department of Water Resources projection extends over the years 1985-2034, while the Kelso, et al., estimate extends over the years 1975-2015.

There are some important similarities between the PAMA and other Active Management Areas which tend to make the PAMA representative of the other areas. The most basic similarity which the PAMA shares with the other Active Management Areas is the ". . . need of comprehensive groundwater management" (Arizona Groundwater Management Study Commission, Summary, June, 1980, p. 2). Also, the pump water areas of the PAMA are characterized by relatively deep pumping lifts. The pumping lifts range from about 600 feet on the eastern side of the PAMA to approximately 400-500 feet on the western side of the PAMA (Hathorn, 1982 and Parsons, 1982, from information based on an early 1970s W.S. Gookin report). In comparison, pumping lifts in deep pumping areas of Pinal County were projected to range between 500-600 feet by 1986 (Boster and Martin, 1977, p. 11).

Description of PAMA Irrigation Districts Presented in this Study

Fourteen major organized irrigation districts lie within the boundary of the PAMA.[1] These fourteen organized districts encompass approximately 318,000 acres of agricultural land. From this total of 14 districts, 8 districts were chosen for this study. The eight districts are Buckeye Irrigation District, Maricopa County Municipal Water Conservation District No. 1, McMicken Irrigation District, Queen Creek Irrigation District, Roosevelt Irrigation District, Roosevelt Water Conservation District, Salt River Project, and Tonopah Irrigation District. The eight districts include approximately 287,000 acres which is roughly 90 percent of the 318,000 ares in the fourteen major districts in the PAMA. The estimated acreage for all crops in Maricopa County was 502,060 in 1980 (Arizona Agricultural Statistics, Historical Summary, 1965-1980). Therefore, the acreage included in the study area is approximately 57 percent of the total estimated acres harvested in Maricopa County in 1980.

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1. There are numerous smaller water companies which lie within the PAMA but these companies and their service territory are not considered in this study since their aggregate impact upon agricultural output in the PAMA is meager.

Roughly 25 percent of surface water is used on the remaining 43 percent of cropland in Maricopa County (recall that roughly 75 percent of the surface water in Maricopa County in 1980 was used in the PAMA based on the preliminary estimates given above). Further, based on the estimates above, just over 50 percent of the groundwater used in Maricopa County in 1980 was used outside the PAMA and, further, since groundwater is used more extensively in the Tucson and Pinal Active Management Areas[2] any potential changes in groundwater use in the PAMA resulting from the 1980 AGWMA may be considered representative of the changes that might occur in other areas of the state which pump groundwater supplies.

The cost of water to farmers in each district varies, as shown in Table 1 below. In the Salt River Project, or SRP, groundwater pumped from district wells has a distinct cost as does the surface water delivered by the district to farmers. By contrast, in the Buckeye Irrigation District, or BID, Roosevelt Irrigation District, or RID, and Roosevelt Water Conservation District, or RWCD, a uniform cost is charged for each acre-foot of water used regardless of whether the water originates as pumped groundwater or surface water. In the RID all the water is pumped groundwater from district-owned wells. In Maricopa County Municipal Water Conservation District, or MCMWCD, a cost of $15 per acre-foot is charged for

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2. Since mostly surface water is evidently used for agriculture in the Prescott Active Management Area, changes in groundwater use will not be reflected as strongly as in the other Active Management Areas of the state.

TABLE 1

COST OF WATER, BY AREA, BY SOURCE TO THE FARMER AT THE FIELD HEAD, 1982

Area	Pumped Groundwater Dollars per Acre Foot	Surface Water Dollars per Acre Foot
Salt River Project	25.00[3]	7.25
Buckeye Irrigation District		7.75[1]
Maricopa County Municipal Water Conservation District	33.25[2]	15.00[1]
Roosevelt Irrigation District		17.50[1]
Roosevelt Water Conservation District		26.00[1]
Queen Creek Irrigation District	64.41[2]	
Tonopah Irrigation District	33.35[2]	
McMicken Irrigation District	53.38[2]	

[1]This charge is for all water delivered to farms in the districts. The water may originate as pumped groundwater and/or surface water. The water is conveyed to district farms through district owned delivery systems.

[2]This charge reflects the total variable cost of pumping groundwater. These costs consist of pump and well repair and maintenance costs and energy costs. The wells in each of these districts are privately owned by the farmer.

[3]This charge reflects the total variable cost of pumping groundwater from district owned wells.

Source: Irrigation district offices and Hathorn and Farr 1982 Arizona Field Crop Budgets, Maricopa County.

water provided from district owned wells or from surface water flow. Additionally, in MCMWCD many district farmers augment water received from the district with water pumped from privately owned wells. Thus, the pumped groundwater charge, shown in Table 1, reflects the total variable cost of pumping water. The cost consists of the total variable cost of pump repair and maintenance and the cost of electric energy to run the pumps. The costs for irrigation water in the Queen Creek Irrigation District, or QCID, Tonopah Irrigation District, or TID, and McMicken Irrigation District, or MID, are for pump repair and maintenance and energy for pumping. The surface water costs and the SRP pump cost for groundwater were obtained from the individual irrigation district offices. The cost for pumped groundwater, excluding the SRP, were taken from Hathorn and Farr (1982) Arizona Field Crop Budgets for Maricopa County. The costs of pump water in MCMWCD and TID are assumed to be equivalent to the total variable costs of pumping water in the Gila Bend area, as found in Hathorn and Farr (1982). The basis for this choice was that in both MCMWCD and TID the foot of lift and the gallons per minute capacity of a typical well in these districts closely approximated the Gila Bend well specifications. Similarly, the cost of pumped groundwater in MID is assumed to be equivalent to the total variable costs for the Rainbow Valley area, as found in Hathorn and Farr (1982), since the typical well in MID closely approximated the typical well in Rainbow Valley. The cost of groundwater in QCID is equal to the total variable costs of pumping for the Queen Creek area, as found in Hathorn and Farr (1982). The typical wells in each of these districts were matched to typical wells found in the budget book (Hathorn and Farr, 1982) under the further assumption that the efficiencies of the pumps in each district were equivalent to the efficiencies assumed in Hathorn and Farr (1982).

Appendix A shows the variable cost of water in the PAMA as a percent of total variable costs for producing a particular crop under surface flood or furrow irrigation technology. The water costs used throughout this study are taken from Table 1 above and are applied to the water needed to produce a given crop with surface flood irrigation technology. Table 2 shows the total variable cost of water as a percent of total variable cost of crop production. The percentages are given for each crop grown in the individual districts.

Table 3 below displays the estimated amounts of groundwater potentially available and the actual average surface water use based on individual district records. Groundwater use has not been monitored in the PAMA in the past, therefore, the amount of groundwater in Table 3 equals an amount that could be (but not necessarily would be) pumped if either district-owned and/or privately owned wells operated according to an assumed schedule: 6 hours per day per month in low-use months (January, February, November, and December), 12 hours per day per month in moderate use months (March, April, September and October) and, 24 hours per day per month in high-use months (May, June, July, and August).

TABLE 2

TOTAL VARIABLE COST OF WATER AS A PERCENT OF TOTAL VARIABLE COST TO PRODUCE A CROP UNDER SURFACE FLOOD IRRIGATION TECHNOLOGY, BY DISTRICT, AND BY CROP

Area	Crop	Total Variable Cost of Water as Percent of Total Variable Cost per Acre	
		------------ % ------------	
		Pump Water	Surface Water
Salt River Project	Alfalfa	57	27
	Upland Cotton	22	8
	Pima Cotton	23	8
	Barley	45	19
	Wheat	37	14
	Sorghum	42	18
	Sugar Beets	25	9
	Safflower	58	28
	Spring Lettuce	2	0.5
	Fall Lettuce	2	0.5
Buckeye Irrigation District	Alfalfa		28
	Upland Cotton		8
	Barley		20
	Wheat		15
	Sorghum		19
Maricopa County Municipal Water Conservation District, No. 1	Upland Cotton	28	15
	Barley	53	33
	Spring Lettuce	2	1
	Fall Lettuce	2	1

(continued)

TABLE 2. (continued)

Area	Crop	Total Variable Cost of Water as Percent of Total Variable Cost per Acre	
		---------- % ----------	
		Pump Water	Surface Water
Roosevelt Irrigation District	Alfalfa	47	
	Upland Cotton	17	
	Pima Cotton	17	
	Barley	37	
	Wheat	29	
	Sugar Beets	19	
	Safflower	49	
Roosevelt Water Conservation District	Alfalfa		57
	Upland Cotton		23
	Pima Cotton		23
	Barley		46
	Wheat		38
	Sorghum		43
	Sugar Beets		26
	Spring Lettuce		2
	Fall Lettuce		2
Queen Creek Irrigation District	Upland Cotton	41	
	Pima Cotton	41	
	Wheat	57	
	Sorghum	62	
Tonopah Irrigation District	Alfalfa	59	
	Upland Cotton	26	
	Wheat	41	
	Barley	49	

(continued)

TABLE 2 (continued)

Area	Crop	Total Variable Cost of Water as Percent of Total Variable Cost per Acre	
		--- % ---	
		Pump Water	Surface Water
McMicken Irrigation District	Upland Cotton	36	
	Wheat	52	
	Barley	61	
	Sugar Beets	40	
	Spring Lettuce	4	
	Fall Lettuce	4	

Source: Representative farm budgets and individual district water costs from district offices and Hathorn and Farr 1982 Arizona Field Crop Budgets, Maricopa County.

TABLE 3

ESTIMATED AVERAGE AMOUNTS OF GROUNDWATER POTENTIALLY AVAILABLE AND ACTUAL AVERAGE SURFACE WATER USE BY AREA, BY AMOUNT OF WATER, AND BY SOURCE OF WATER

Area	Amount of Water (Acre Feet)			Source of Water			
	District Pumped Groundwater	Private Farm Pumped Groundwater	District Delivered Surface Water	District Wells	Private Wells	River Diversion	Other (e.g., effluent)
Salt River Project[1]	497,085		406,851	X		X	
Buckeye Irrigation District[2]	112,840		156,072	X		X	X
Maricopa County Municipal Water Conservation District[3]	166,974	197,084	40,728	X	X	X	
Roosevelt Irrigation District[4]	279,203			X			
Roosevelt Water Conservation District[5]	161,500		127,371	X		X	
Queen Creek Irrigation District[6]		230,966			X		
Tonopah Irrigation District[7]		133,616			X		
McMicken Irrigation District[8]		375,399			X		
Total	1,217,602	937,065	731,022	X	X	X	X
Grand Total	2,885,689						

(continued)

TABLE 3 (continued)

[1]Average amounts of surface and groundwater estimated from 1968-1981 data.

[2]Average amounts of surface and groundwater estimated from 1981 data. The surface flow obtained from the Gila River is furnished by Salt River Project as a result of a settlement reached in 1943. Approximately 2,500 acre-feet of sewage effluent is received per month under a 40-year agreement.

[3]Average amounts of surface and groundwater estimated from 1977-1981 data.

[4]Average amount of groundwater estimated from 1970-1980 data. 1977-1980 values estimated from 1970-1976 actual values.

[5]Average amounts of groundwater estimated from 1975-1981 data.

[6]Average amount of groundwater estimated from 1975-1980 data.

[7]Average amount of groundwater estimated from information obtained from Doug Toy, engineer, of Franzoy, Corey, and Associates.

[8]Average amount of groundwater estimated from information obtained from Walt Parsons, Arizona Department of Water Resources.

Source: Irrigation district records, personal communication with Franzoy, Corey, and Associates engineer, personal communication with Arizona Department of Water Resources water specialist, and DeCook et al., 1978.

This pumping schedule is assumed to reasonably represent a possible schedule that a typical district might follow throughout a year. The pumping schedule was developed after conversations with several irrigation districts, included in this study, about the type of pump schedule that each follows. The pump schedule, used in this study, is an average schedule based on this information. More will be said about this schedule later. Introducing the schedule here allows an estimate to be made of the potential amounts of groundwater that could be pumped in each district in the PAMA. Table 3 shows that of the grand total of 2.88 million acre-feet of water potentially available in the study area, 75 percent is from groundwater and 25 percent is from surface water.

Description of Districts[3] in Study Area

Each individual irrigation district included in this study is briefly described below.

Buckeye Irrigation District (BID)

The Buckeye Irrigation District located west of Phoenix was legally formed in 1922, although water rights to water from the Gila River were acquired in 1885. Water is delivered to district farms through district owned canals. In 1975, it was estimated that 65,337 acre-feet of groundwater and 74,681 acre-feet of surface water and effluent were consumed by the districts. Treated sewage effluent is

3. A brief description of each district can be found in DeCook et al., 1978. This section draws from that study.

procured by the district through a long-standing 40-year contract with the city of Phoenix. A curiosity about BID is a "water problem" not encountered in other districts--namely land requiring drainage of excess water into the Gila River. As a consequence of this overabundance of water, BID has not filed an application for CAP[4] water. Principal crops in the district in 1982 included alfalfa, Upland cotton, barley, wheat and sorghum. The district encompasses roughly 18,000 acres of cropped land.

Maricopa County Municipal Water Conservation District No. 1 (MCMWCD No. 1)

MCMWCD No. 1 is also located west of Phoenix and north of BID. Pumped groundwater supplies come from district owned wells. The district was formed in 1925 and financed the construction of Waddell Dam (formerly Carl Pleasant Dam) on the Agua Fria River. The district owns a water right to approximately 188,000 acre feet of water from the River. Additionally, district owned wells pump groundwater supplies within the district. Privately owned wells also operate within the district. In 1977, an estimated 47,931 acre-feet of water were applied to crops, of which 16,495 acre-feet came from Waddell Dam, and 31,436 acre-feet were pumped from wells (this does not include private pumping of groundwater which was estimated to be about 47,000 acre-feet) (MCMWCD No. 1 district office).

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4. CAP water is Central Arizona Project Water. The CAP is a multi-billion dollar project designed to bring Colorado River water to the desert cities of Arizona--Phoenix and Tucson--and also to agricultural areas in Central and Southern Arizona.

Roughly 33,600 acres are contained in the district. In 1983, the principal crops were Upland cotton, barley, lettuce and citrus.

McMicken Irrigation District (MID)

This district is one of several that were created to obtain Central Arizona Project (CAP) water allocations. McMicken District was formed in 1964, even though it is reported (DeCook et al., 1978) that groundwater pumping began in the area, which is located west of Phoenix adjacent to MCMWCD No. 1, as early as 1912.

All groundwater supplies are pumped by privately owned wells. The estimated 1978 groundwater pumpage was 155,000 acre-feet. The district encompasses about 35,000 acres with Upland cotton, barley, wheat, sugar beets, lettuce and citrus, the principal crops grown in 1982.

Queen Creek Irrigation District (QCID)

Queen Creek Irrigation District is situated to the south and east of Phoenix. This district has applied for CAP water and has been in existence since 1923. It was originally formed to obtain electrical power to operate irrigation pumps. QCID continues to obtain power (through contract) from the Salt River Project.

Water consumed for crop irrigation in the district is obtained entirely from privately owned farm wells.

Acreage estimates within the QCID vary from between 22,500 and 23,500 acres. In 1977, 23,411 acres were assessed for tax purposes.

Estimated groundwater pumpage records are unavailable. The primary crops in QCID were Upland cotton, Pima cotton, wheat and grain sorghum with some potatoes, grapes and citrus also being grown.

Roosevelt Irrigation District (RID)

Roosevelt Irrigation District formed in 1923 lies to the west of Phoenix and lies to the north of and adjacent to Buckeye Irrigation District. Water is obtained entirely from groundwater supplies. The water is delivered from district owned wells by district owned canal systems to farms. It was estimated that 152,000 acre-feet of groundwater were consumed in RID in 1977. RID has also applied for CAP water.

The district encompasses roughly 35,000 acres. The predominant crops were alfalfa, Upland cotton, Pima cotton, barley, wheat, sugar beets and safflower in 1982.

Roosevelt Water Conservation District (RWCD)

Roosevelt Water Conservation District is located south and east of Phoenix. The district adopted the present name in 1923, though an organized district was formed in 1917. Approximately 30 percent of RWCD's water is obtained through a contract with the Salt River Project from the Salt-Verde River system. The remaining 70 percent is pumped groundwater. Water consumed in the district is delivered to the district farms through a system of district owned canals. RWCD has filed an application for CAP water.

District land available for crop production was estimated to be about 37,000 acres in 1976. An average of between 125,000 to 135,000 acre-feet per year was delivered to district land between 1973-1977. The chief crops grown in the area included alfalfa, Upland cotton, Pima cotton, barley, wheat, sorghum, sugar beets and lettuce in 1982.

Salt River Project (SRP)

The Salt River Project takes in the Phoenix metropolitan area. SRP is by far the largest district in this study. The district also provides power to much of the southern metropolitan region and outlying areas such as Queen Creek in addition to water for nonagricultural and agricultural users.

SRP obtains water from a series of six dams on the Salt-Verde River system. Also the district owned wells provide groundwater supplies. An extensive canal system delivers water supplies within the district. An estimated 910,506 acre-feet of surface water and groundwater were consumed in 1977. The SRP has filed an application for CAP water.

The cropped area has been decreasing over time due to urban expansion. Between 1976 and 1977 an estimated 2,764 acres of agricultural land were converted to urban uses (DeCook et al., 1978). In 1977 approximately 106,800 acres of cropped land were irrigated. The chief crops grown in the SRP included alfalfa, Upland cotton, Pima cotton, barley, wheat, sorghum, sugar beets, lettuce and safflower in 1982. In addition, bermuda and sudan grass pasture, truck crops (excluding lettuce), citrus, soybeans, peas and nursery flowers were also grown in the area in 1982.

Tonopah Irrigation District (TID)

This district lies farthest west of Phoenix of all the districts in this study and is the "newest" district having been formed in 1977 expressly to obtain CAP water. Consequently, few records exist on district operations.

Water consumed in the district is derived entirely from groundwater pumped from private wells. Insufficient records exist on pumpage in TID. Cropped acreage is estimated to be roughly 16,000 acres. The chief crops grown in the district were alfalfa, Upland cotton, barley and wheat in 1982.

CHAPTER 2

ECONOMIC ANALYSIS

The economic analysis of this study centers on profit maximization from crop production in each of eight irrigation districts in the PAMA. The maximization is constrained by the availability of resources such as land, water, and capital for investment. The economic analysis is explored by means of the familiar constrained profit maximization model of the firm. In this case, the firm is assumed to be the entire collection of farms within a particular irrigation district. The analysis is a static analysis in the sense that the maximization of profits in only one particular year is considered. The effects of the imposition of the pump tax and water duty policies of the 1980 AGWMA in the PAMA, and the impacts of changes in these policies upon profits at certain specified points in time are examined. The factors that change within the profit maximization model, as a result of the pump tax and water duty policies, are the cost of groundwater and the physical amounts of groundwater that can be pumped in an irrigation district at different points in time. Either the cost of groundwater or the physical amounts of groundwater that may be pumped are changed with other conditions such as output prices and other input costs held constant. Therefore, a new static relationship occurs at the new points in time. The qualitative effects on profits and groundwater use, resulting from the change in either the cost of water or the amounts of groundwater that can be pumped at a new point in time, are summarized using comparative statics.

The objective function of the economic model can be stated as: maximizing total district profits by choosing the number of acres of each crop using a particular irrigation technology on a particular soil type subject to resource constraints. The objective function can be written algebraically as:

$$\underset{(A_{ijk})}{\text{Maximize}}\ \Pi = \sum_i \sum_j \sum_k \Pi_{ijk}(A_{ijk}) \cdot A_{ijk} \tag{1}$$

where,

Π = total irrigation district profits

i = crop i

j = irrigation technology j

k = soil type k

$\Pi_{ijk}(A_{ijk})$ = profit per acre for crop i using irrigation technology j on soil type k which is a function of A_{ijk}

A_{ijk} = number of acres chosen of crop i using irrigation technology j on soil type k.

The maximization of district profits, Π, is accomplished subject to the following constraints:

$$\sum_i \sum_j \sum_k A_{ijk} \leq \overline{A}_k \tag{2}$$

$$\sum_i \sum_j \sum_k A_{ijk} \cdot W^g_{ijk} \leq \overline{W}_{gw} \tag{3}$$

$$\sum_i \sum_j \sum_k A_{ijk} \cdot W^s_{ijk} \leq \overline{W}_{sw} \tag{4}$$

$$\sum_i \sum_k A_{ijk} \geq \overline{A}_j \tag{5}$$

$$\sum_i \sum_j \sum_k (A_{ijk} - \overline{A}_j) \cdot \overline{C}_j \leq \overline{I} \tag{6}$$

$$\sum_j \sum_k A_{ijk} \geq \underline{\beta} \tag{7}$$

$$\sum_j \sum_k A_{ijk} \leq \overline{\beta} \tag{8}$$

$$A_{ijk} \geq 0 \tag{9}$$

where,

$\overline{A}_j$ = number of acres of technology j "inherited" from an earlier period

$\overline{A}_k$ = total acreage of soil type k available in an irrigation district

W^s_{ijk} = amount of surface water applied per acre to crop i using irrigation technology j on soil type k

W^g_{ijk} = amount of groundwater applied per acre to crop i using irrigation technology j on soil type k

$\overline{W}_{sw}$ = total amount of surface water available for irrigation

$\overline{W}_{gw}$ = total amount of groundwater available for irrigation

$\overline{I}$ = amount of capital available for investment in irrigation technologies in a time period

$\overline{C}_j$ = constant dollar cost per acre for investment in technology j

$\underline{\beta}$ = minimum number of acres of a crop grown in a time period

$\overline{\beta}$ = maximum number of acres of a crop grown in a time period

The first three constraints are resource constraints on total land and water use. The total amount of groundwater and surface water available for irrigation is restrained by the second and third constraints, respectively. The fourth constraint "carries over" the number of acres of a particular technology adopted in an earlier period or time by requiring that the number of acres adopted earlier be used in the current time period. The fifth constraint limits the amount of capital funds available for use in irrigation technology investment in a particular time period for acres in excess of the A_j, or the number of acres "inherited" from an earlier period. The sixth constraint requires that a minimum number of acres of a crop be grown in a time period, while the seventh constraint requires that no more than a certain maximum number of acres of a crop be grown in a time period. The sixth and seventh constraints are sometimes called "flexibility constraints." These constraints are explained in detail in later sections, but, at this point, these constraints can be thought of as placing limits on the rate at which acres of crops can be expanded or contracted in a time period. Finally, the eighth constraint is a non-negativity constraint which stipulates that the production of a negative amount of acres of a crop is impossible.

The problem is maximizing (1) subject to constraints (2)-(9). Assuming that the objective function (1) is twice differentiable, quasi-concave, and increasing in the A_{ijk}'s, and the constraints (2)-(8) are twice differentiable, and convex, the Kuhn-Tucker conditions can be used to characterize the optimum condition. The problem can be written in the familiar Lagrangean form as:

$$\underset{(A_{ijk})}{\text{Maximize}}\ \Pi = \sum_i \sum_j \sum_k \Pi_{ijk}(A_{ijk}) \cdot A_{ijk} + \lambda_1(A_k - \sum_i \sum_j \sum_k A_{ijk})$$
$$+ \lambda_2(\overline{W}_{gw} - \sum_j \sum_j \sum_k A_{ijk} \cdot W^g_{ijk}) + \lambda_3(\overline{W}_{sw} - \sum_i \sum_j \sum_k A_{ijk} \cdot W^s_{ijk})$$
$$+ \lambda_4(\sum_i \sum_k A_{ijk} - \overline{A}_j) + \lambda_5(\overline{T} - \sum_i \sum_j \sum_k (A_{ijk} - \overline{A}_j) \cdot \overline{C}_j)$$
$$+ \lambda_6(\sum_j \sum_k A_{ijk} - \underline{\beta}) + \lambda_7(\overline{\beta} - \sum_j \sum_k A_{ijk}) \qquad (10)$$

The first order conditions, or FOC, for a profit maximum, assuming an interior solution to the Kuhn-Tucker conditions, choosing the A_{ijk}'s, are:

$$\frac{\partial \Pi}{\partial A_{ijk}} = \left(\Pi_{ijk} + A_{ijk} \cdot \frac{\partial \Pi_{ijk}}{\partial A_{ijk}}\right) - \lambda_1 - \lambda_2 \cdot W^g_{ijk} - \lambda_3 \cdot W^s_{ijk}$$
$$+ \lambda_4 - \lambda_5 \cdot \overline{C}_j + \lambda_6 - \lambda_7 = 0 \text{ (for all i,j,k.)} \qquad (11)$$

The decision makers (the farmers in each district, in this case) should choose a vector of crop-soil-irrigation systems, A^*_{ijk}'s such that, $\frac{\partial \Pi}{\partial A_{ijk}} = 0$. The A^*_{ijk}'s are the optimal values of A_{ijk} which maximize (1) above.

The right hand side of (11) consists of the Π_{ijk} which is the marginal profit per acre from crop i using irrigation technology j on soil k, the Lagrangean multipliers, or the λ's, from each constraint, and the water applied per acre for crop i using irrigation technology j on soil type k, W_{ijk}, and the dollar cost per acre for technology j on soil type k for crop i, $\bar{C}_j$. The Lagrangean multipliers can be interpreted as shadow prices (see Silberberg, 1978, for interpretation of Lagrangean multipliers). The Lagrangean multipliers, or shadow prices, indicate how much the objective function value, district profits, Π, in this case, would change if the constraint with which a particular multiplier is associated is decreased or increased by one unit. For example, λ_1 indicates by how much Π would change if the total acreage of a particular soil type k within a district were increased or decreased by one acre. The multiplier $\lambda_5 \cdot \bar{C}_j$ indicates by how much Π would change if the capital available for investment, $\bar{I}$, were changed by one unit. In other words, the marginal profit per acre from investment, $\frac{\partial \Pi}{\partial I^*}$, equals the value of the multiplier λ_5 times the per acre cost of technology j or $\bar{C}_j$.

The FOC, of the profit maximization problem, expressed in (11) above must hold for each irrigation district and for each crop, technology, and soil combination. For given crop output prices and input costs, marginal profits within any district should be made equal to each other, for all crop, technology, and soil combinations, in order to maximize the total profit in each district from the production of all crops. In other words, total profits from crop production, in any district, are maximized if marginal profits arising from production of these crops are allocated according to the equi-marginal principle. The equi-marginal principle is illustrated in Figure 1 below for an irrigation district with 2 crop-soil-technology activities. Marginal profits, Π_1 and Π_2, from the two activities, are equated given a cost of pw for groundwater.

Given constant output prices and input costs, total profits are maximized when the marginal profits per acre for each crop, technology and soil combination are equated according to the equi-marginal principle. Since the marginal profit functions of (11), the Π_{ijk}'s, are functions of the A_{ijk}'s, the marginal profit functions are downward sloping, instead of being horizontal straight lines at a given cost of groundwater. The marginal profit functions would be horizontal if they were assumed to be constant.

The Pump Tax

How may the profits of an irrigation district change, if the cost of groundwater increases when a pump tax is levied, as in the 1980 AGWMA? The pump tax policy of the 1980 AGWMA is examined in the context of the profit maximization model by allowing the cost of groundwater, pw, to increase. In order to examine this question more fully, the Π_{ijk}'s, must be expressed in terms of the parameters of the model, because the Π_{ijk}'s are functions of these

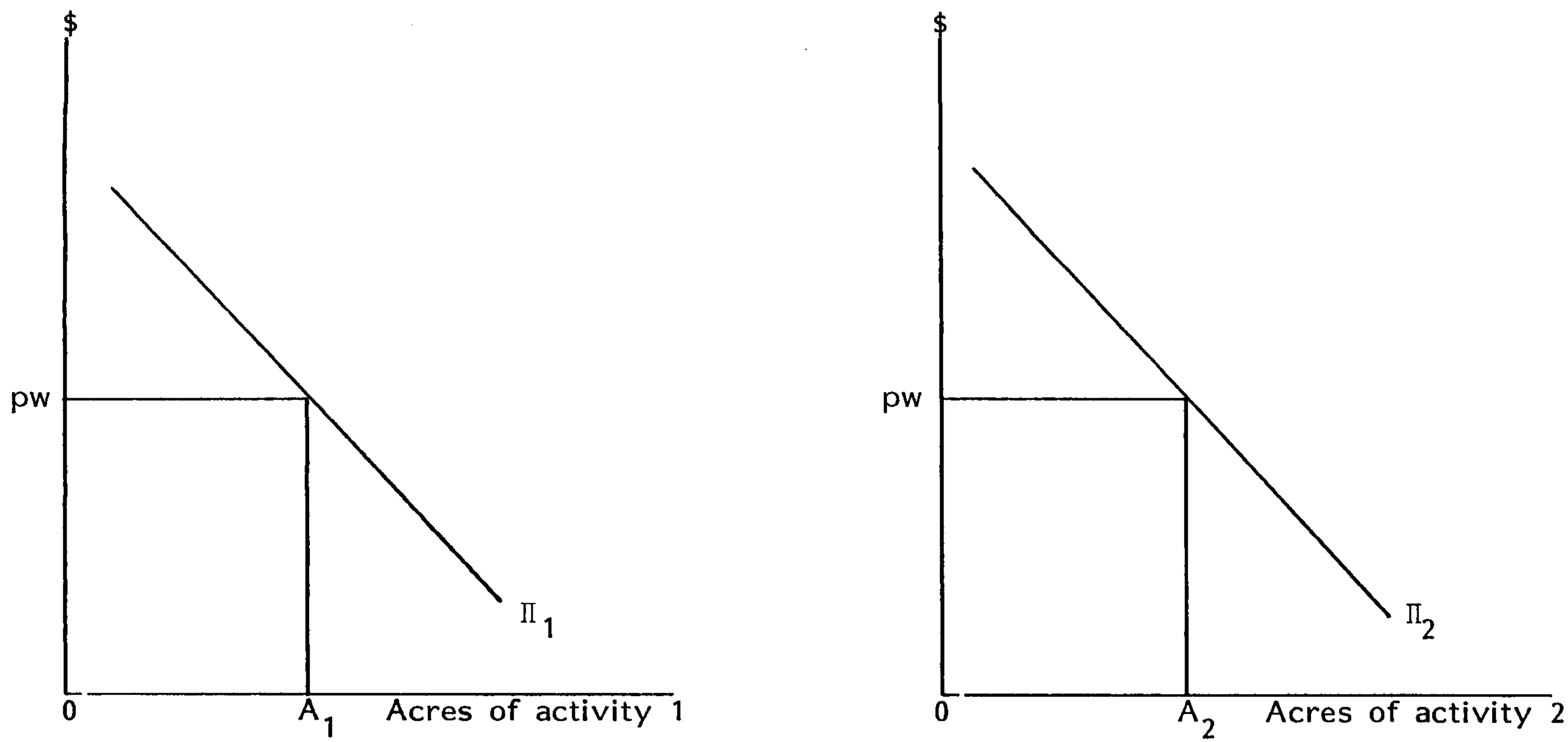

Fig. 1. Illustration of Equi-Marginal Principle for a Profit-Maximizing Irrigation District With 2 Crop-Soil-Technology Activities (hypothetical).

parameters. Once it has been determined how the marginal profits change when the cost of groundwater increases, it is straightforward to determine changes in Π, or district profits, since Π is a function of the marginal profits, or Π_{ijk}.

If the second-order conditions, or SOC, for a profit maximum hold, that is, if in (11), $\frac{\partial^2 \Pi}{\partial A_{ijk}^2} \leq 0$, for all i,j,k, then a static equilibrium exists and (10) can be solved for changes in the parameters of the model. The marginal profit functions can be expressed as functions of the parameters of the problem (10) as follows:

$$\Pi_{ijk} = \Pi^*_{ijk}(p_i, pw, \overline{\Gamma}, \overline{A}_k, \underline{\beta}, \overline{\beta}, \overline{A}_j, \overline{W}_{gw}, \overline{W}_{sw}, \overline{C}_j) \quad (12)$$

where,

Π^*_{ijk} = the equilibrium value of Π_{ijk} that maximizes (11)

p_i = the constant market price for a crop

pw = the cost of groundwater

The A_{ijk}'s, W_{ijk}'s, and the Lagrangean multipliers, the λ's, are also functions of the parameters of the problem. The explicit relations in (12) may be substituted into (11) to give:

$$\frac{\partial \Pi}{\partial A_{ijk}} = \Big[\Pi^*_{ijk}(p_i, pw, \overline{\Gamma}, \overline{A}_k, \underline{\beta}, \overline{\beta}, \overline{A}_j, \overline{W}_{gw}, \overline{W}_{sw}, \overline{C}_j)$$

$$+ A^*_{ijk}(p_i, pw, \overline{\Gamma}, \overline{A}_k, \underline{\beta}, \overline{\beta}, \overline{A}_j, \overline{W}_{gw}, \overline{W}_{sw}, \overline{C}_j) \cdot$$

$$\frac{\partial \Pi^*_{ijk}}{\partial A^*_{ijk}}(p_i, pw, \overline{\Gamma}, \overline{A}_k, \underline{\beta}, \overline{\beta}, \overline{A}_j, \overline{W}_{gw}, \overline{W}_{sw}, \overline{C}_j)\Big]$$

$$- \lambda_1^*(p_i,\ pw,\ \bar{I},\ \bar{A}_k,\ \underline{\beta},\ \bar{\beta},\ \bar{A}_j,\ \bar{W}_{gw},\ \bar{W}_{sw},\ \bar{C}_j)$$

$$- \lambda_2(p_i,\ pw,\ \bar{I},\ \bar{A}_k,\ \underline{\beta},\ \bar{\beta},\ \bar{A}_j,\ \bar{W}_{gw},\ \bar{W}_{sw},\ \bar{C}_j) \cdot$$

$$W_{ijk}^{g*}(p_i,\ pw,\ \bar{I},\ \bar{A}_k,\ \underline{\beta},\ \bar{\beta},\ \bar{A}_j,\ \bar{W}_{gw},\ \bar{W}_{sw},\ \bar{C}_j)$$

$$- \lambda_3^*(p_i,\ pw,\ \bar{I},\ \bar{A}_k,\ \underline{\beta},\ \bar{\beta},\ \bar{A}_j,\ \bar{W}_{gw},\ \bar{W}_{sw},\ \bar{C}_j) \cdot$$

$$W_{ijk}^{s*}(p_i,\ pw,\ \bar{I},\ \bar{A}_k,\ \underline{\beta},\ \bar{\beta},\ \bar{A}_j,\ \bar{W}_{gw},\ \bar{W}_{sw},\ \bar{C}_j)$$

$$+ \lambda_4^*(p_i,\ pw,\ \bar{I},\ \bar{A}_k,\ \underline{\beta},\ \bar{\beta},\ \bar{A}_j,\ \bar{W}_{gw},\ \bar{W}_{sw},\ \bar{C}_j)$$

$$- \lambda_5^*(p_i,\ pw,\ \bar{I},\ \bar{A}_k,\ \underline{\beta},\ \bar{\beta},\ \bar{A}_j,\ \bar{W}_{gw},\ \bar{W}_{sw},\ \bar{C}_j) \cdot \bar{C}_j$$

$$+ \lambda_6^*(p_i,\ pw,\ \bar{I},\ \bar{A}_k,\ \underline{\beta},\ \bar{\beta},\ \bar{A}_j,\ \bar{W}_{gw},\ \bar{W}_{sw},\ \bar{C}j)$$

$$- \lambda_7^*(p_i,\ pw,\ \bar{I},\ \bar{A}_k,\ \underline{\beta},\ \bar{\beta},\ \bar{A}_j,\ \bar{W}_{gw},\ \bar{W}_{sw},\ \bar{C}_j) = 0 \qquad (13)$$

Assuming that (11) possesses continuous derivatives and that the partial derivatives of (11) with respect to the parameter pw are non zero the expression in (12) is legitimate.

The expression in (13) may be differentiated with respect to the parameter pw in order to ascertain the effects on profit of an increase in the cost of groundwater as proposed in the AGWMA. Differentiating (13) with respect to pw gives:

$$\frac{\partial \Pi^*_{ijk}}{\partial pw} + \left[\frac{\partial A_{ijk^*}}{\partial pw} \cdot \frac{\partial \Pi_{ijk^*}}{\partial A_{ijk^*}} + A_{ijk^*} \cdot \frac{\partial^2 \Pi^*_{ijk}}{\partial A_{ijk^*} \partial pw} - \frac{\partial \lambda^*_2}{\partial pw}\right]$$

$$-\left[\frac{\partial \lambda^*_2}{\partial pw} \cdot W^g_{ijk*} + \lambda^*_2 \cdot \frac{\partial W^{g*}_{ijk}}{\partial pw}\right] - \left[\frac{\partial \lambda^*_3}{\partial pw} \cdot W^s_{ijk^*} + \lambda^*_3 \cdot \frac{\partial W^{s*}_{ijk}}{\partial pw}\right] + \frac{\partial \lambda^*_4}{\partial pw}$$

$$-\frac{\partial \lambda^*_5}{\partial pw} \cdot \bar{C}_j + \frac{\partial \lambda^*_6}{\partial pw} - \frac{\partial \lambda^*_7}{\partial pw} = 0 \qquad (14)$$

The product rule was applied to the second, third, and fourth terms. Solving for $\frac{\partial \Pi^*_{ijk}}{\partial pw}$ gives the desired derivative:

$$\frac{\partial \Pi^*_{ijk}}{\partial pw} = - \left[\frac{\partial A_{ijk^*}}{\partial pw} \cdot \frac{\partial \Pi_{ijk^*}}{A_{ijk^*}} + A_{ijk^*} \cdot \frac{\partial^2 \Pi^*_{ijk}}{\partial A_{ijk^*} \partial pw}\right]$$

$$-\left[\frac{\partial \lambda^*_1}{\partial pw} + \frac{\partial \lambda^*_2}{\partial pw} \cdot W^g_{ijk*} + \lambda^*_2 \cdot \frac{\partial W^g_{ijk*}}{\partial pw}\right]$$

$$+\left[\frac{\partial \lambda^*_3}{\partial pw} \cdot W^s_{ijk^*} + \lambda^*_3 \cdot \frac{\partial W^{s*}_{ijk}}{\partial pw}\right] - \frac{\partial \lambda^*_4}{\partial pw} + \frac{\partial \lambda^*_5}{\partial pw} \cdot \bar{C}_j - \frac{\partial \lambda^*_6}{\partial pw} + \frac{\partial \lambda^*_7}{\partial pw} \qquad (15)$$

Mathematically, the result in (15) may be greater than, equal to, or less than zero depending upon the relative magnitudes of the terms in (15). Economically, something can be said about the change in the marginal profit functions given a change in the cost of groundwater. When the cost of groundwater increases the best that can be hoped for is that the marginal profit functions would not change. However, it is more typical to expect that the marginal profit functions will shift inward. The rise in the cost of groundwater will decrease the marginal profits from any crop-soil-technology activity. However, the inward shift of the marginal profit functions can be offset to some degree by changes in the shadow prices, the λ^{*}'s, in (15). Consider, for example, $\frac{\partial \lambda_5^*}{\partial pw} \cdot \bar{C}_j$, which is the change in the shadow price of investment in new irrigation technologies due to an increase in the cost of groundwater times the constant per acre cost of investment. If it becomes more profitable to invest in more efficient irrigation technologies as a result of an increase in the cost of groundwater, the term $\frac{\partial \lambda_5^*}{\partial pw} \cdot \bar{C}_j$ would offset the inward shift of the marginal profit function to some degree. Just how much the inward shift of the marginal profit function is offset depends upon the relative magnitude of $\frac{\partial \lambda_5^*}{\partial pw} \cdot \bar{C}_j$. However, a priori it can be said that the shadow price effects will be more than offset by $\frac{\partial \Pi_{ijk}^*}{\partial pw}$. Since nothing would have prevented adoption of new technologies with a lower cost of water to increase original profits, it cannot be expected that adoption of new technologies will occur at a higher cost of water such that $\frac{\partial \Pi_{ijk}^*}{\partial pw}$ is totally offset thus, resulting in an increase in marginal profits. The best that can be expected is a situation depicted in Figure 2 in which the dotted line represents the shadow price effect of investment in new irrigation technology.

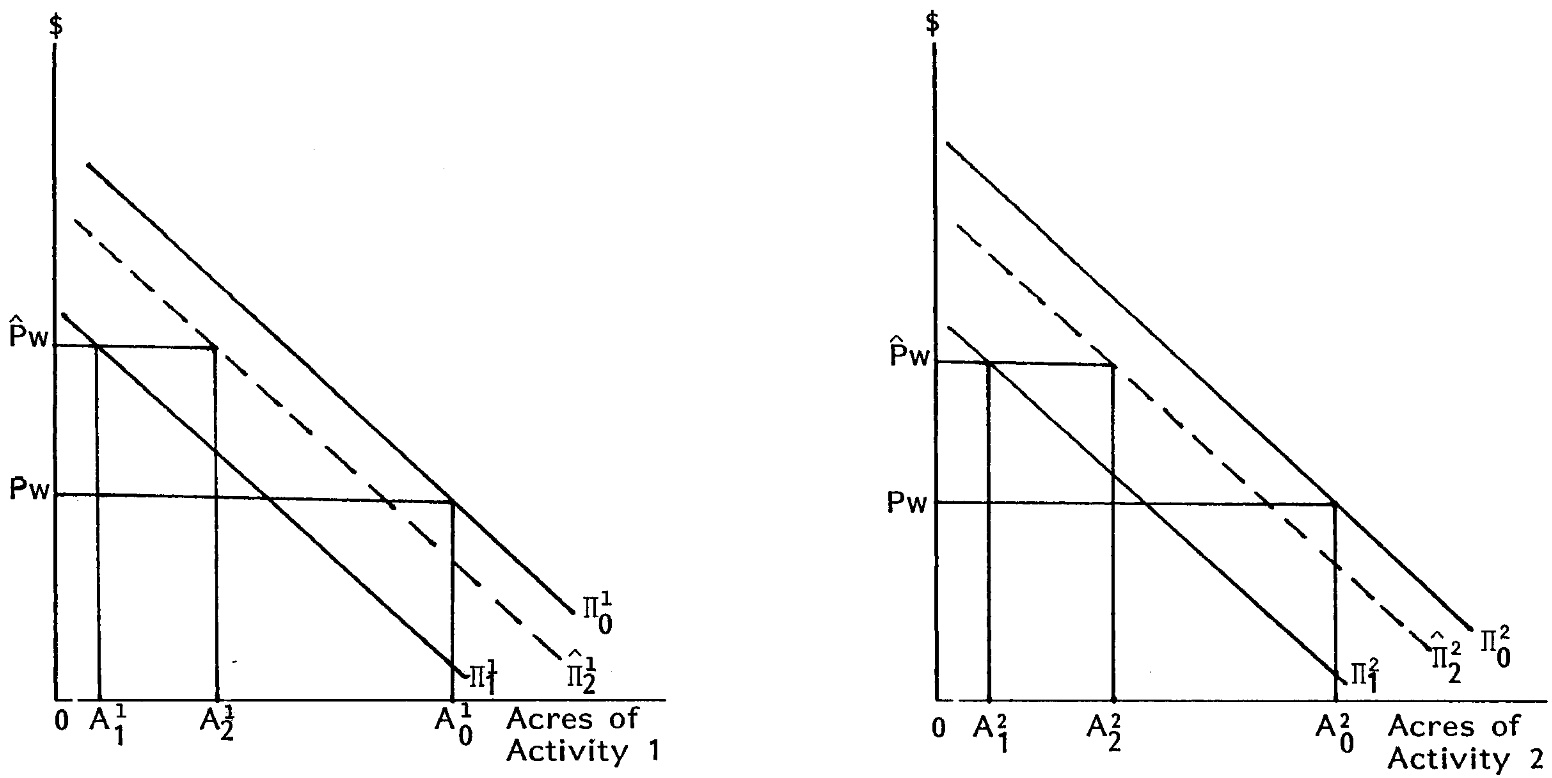

Fig. 2. Illustration of Changes in Marginal Profits When the Cost of Groundwater Increases For A Profit-Maximizing Irrigation District and Possible Offsetting Effects of Investment in New Irrigation Technology (hypothetical).

As shown, investment has offset the inward shift of the marginal profit function from Π_1^1 to $\hat{\Pi}_2^1$ and from Π_1^2 to $\hat{\Pi}_2^2$.

Similarly, the effects of changes in the proposed pump tax on water use (groundwater use, in this case), the W_{ijk}^{g*}'s can be determined. Beginning with (13) the W_{ijk}^{g*}'s can be expressed as functions of the parameters of the model. Expression (13) can be differentiated with respect to pw to give expression (16). Solving for $\frac{\partial W^g_{ijk*}}{\partial pw}$ gives:

$$\frac{\partial W^g_{ijk*}}{\partial pw} = \left[\frac{\partial \Pi_{ijk}}{\partial pw} + \left\{ \frac{\partial A^*_{ijk}}{\partial pw} \cdot \frac{\partial \Pi^*_{ijk}}{\partial pw} + A^*_{ijk} \cdot \frac{\partial^2 \Pi_{ijk}}{\partial A_{ijk*} \partial pw} \right\} \right.$$

$$\left. - \frac{\partial \lambda_1^*}{\partial pw} - \frac{\partial \lambda_2^*}{\partial pw} \cdot W^g_{ijk*} - \left[\frac{\partial \lambda_3^*}{\partial pw} \cdot W^s_{ijk*} + \lambda_3^* \cdot \frac{\partial W^s_{ijk*}}{\partial pw} \right] + \frac{\partial \lambda_4^*}{\partial pw} - \frac{\partial \lambda_5^*}{\partial pw} \cdot \bar{C}_j + \frac{\partial \lambda_6^*}{\partial pw} - \frac{\partial \lambda_7^*}{\partial pw} \right] \Bigg/ \lambda_2^* \qquad (16)$$

Mathematically, the expression in (16) can be greater than, equal to, or less than zero. But economically, the expected result is that $\frac{\partial W^g_{ijk*}}{\partial pw}$ is negative--an increase in the cost of groundwater leads to a decrease in groundwater withdrawals.

The Water Duty

The change in groundwater cost is a market effect. The other proposed policy of the 1980 AGWMA considered in this study, an irrigation water duty, has a non-market effect upon the use of groundwater. That is, the irrigation water duty creates a non-market barrier beyond which no groundwater may be used for irrigation. In order to examine the possible effects of the irrigation water duty, expression (13) is utilized once more. Differentiating (13) with respect to $\overline{W}_{gw}$ and solving for $\frac{\partial \Pi^*_{ijk}}{\partial \overline{W}_{gw}}$ gives:

$$\frac{\partial \Pi^*_{ijk}}{\partial \overline{W}_{gw}} = - \left[\frac{\partial A^*_{ijk}}{\partial \overline{W}_{gw}} \cdot \frac{\partial \Pi^*_{ijk}}{\partial A^*_{ijk}} + A^*_{ijk} \cdot \frac{\partial^2 \Pi^*_{ijk}}{\partial A^*_{ijk} \, \partial \overline{W}_{gw}} \right]$$

$$+ \frac{\partial \lambda^*_1}{\partial \overline{W}_{gw}} + \left[\frac{\partial \lambda^*_2}{\partial \overline{W}_{gw}} \cdot W^{g*}_{ijk} + \lambda^*_2 \cdot \frac{\partial W^{g*}_{ijk}}{\partial \overline{W}_{gw}} \right]$$

$$+ \left[\frac{\partial \lambda^*_3}{\partial \overline{W}_{gw}} \cdot W^{s*}_{ijk} + \lambda^*_3 \cdot \frac{\partial W^{s*}_{ijk}}{\partial \overline{W}_{gw}} \right] - \frac{\partial \lambda^*_4}{\partial \overline{W}_{gw}} + \frac{\partial \lambda^*_5}{\partial \overline{W}_{gw}} \cdot \overline{C}_j$$

$$- \frac{\partial \lambda^*_6}{\partial \overline{W}_{gw}} + \frac{\partial \lambda^*_7}{\partial \overline{W}_{gw}} \qquad (17)$$

Again the product rule was applied as in (14).

In this case, the sign of $\frac{\partial \Pi^*_{ijk}}{\partial \overline{W}_{gw}}$ is mathematically indeterminate as was the case for the sign of $\frac{\partial \Pi^*_{ijk}}{\partial pw}$ in (14). However, in terms of economics, the imposition of a water duty will cause the marginal profit function for a crop-soil-technology activity to shift inward as shown in Figure 2. However, the shadow price effect of investment in new irrigation technologies may offset this inward shift of the marginal profit function as shown by the dotted line in Figure 2.

The effect of the irrigation water duty on groundwater withdrawal can be expressed as follows:

$$\frac{\partial W^{g*}_{ijk}}{\partial \overline{W}_{gw}} = \left[\frac{\partial \Pi^*_{ijk}}{\partial \overline{W}_{gw}} + \left\{\frac{\partial A^*_{ijk}}{\partial \overline{W}_{gw}} \cdot \frac{\partial \Pi^*_{ijk}}{\partial A^*_{ijk}} + A^*_{ijk} \cdot \frac{\partial^2 \Pi^*_{ijk}}{\partial A_{ijk^*} \partial \overline{W}_{gw}}\right\}\right] - \frac{\partial \lambda^*_1}{\partial \overline{W}_{gw}}$$

$$- \frac{\partial \lambda^*_2}{\partial \overline{W}_{gw}} - \left[\frac{\partial \lambda^*_3}{\partial \overline{W}_{gw}} \cdot W^{s*}_{ijk} + \lambda^*_3 \cdot \frac{\partial W^{s*}_{ijk}}{\partial \overline{W}_{gw}}\right]$$

$$+ \frac{\partial \lambda^*_4}{\partial \overline{W}_{gw}} - \frac{\partial \lambda^*_5}{\partial \overline{W}_{gw}} \cdot \overline{C}_j + \frac{\partial \lambda^*_6}{\partial \overline{W}_{gw}} - \frac{\partial \lambda^*_7}{\partial \overline{W}_{gw}} \Big/ \lambda^*_2 \qquad (18)$$

Again the expression in (18) is mathematically indeterminate in sign depending on the relative magnitudes of the parameters. But, economically, the expected result is that (18) is negative.

The effects of a proposed pump tax and/or water duty on total district profits, Π, can be ascertained from the effects of those proposed policies on the per acre marginal profits for each crop i using technology j on soil type k.

Total district profits are a function of the per acre profits from each crop i grown in a particular district. That is,

$$\Pi = \Pi(\Pi_{ijk}) \tag{19}$$

From (12), Π_{ijk} can be expressed in terms of the parameters of the model. So (19) can be rewritten as:

$$\Pi = \Pi\left[\Pi_{ijk}(p_i,\ pw,\ \bar{T},\ \bar{A}_k,\ \underline{\beta},\ \bar{\beta},\ \bar{A}_j,\ \bar{W}_{gw},\ \bar{W}_{sw},\ \bar{C}_j)\right] \tag{20}$$

Differentiating (20) with respect to pw and $\bar{W}_{gw}$ respectively gives:

$$\frac{\partial \Pi}{\partial pw} = \frac{\partial \Pi}{\partial \Pi^*_{ijk}} \cdot \frac{\partial \Pi^*_{ijk}}{\partial pw} \tag{21}$$

and,

$$\frac{\partial \Pi}{\partial \bar{W}_{gw}} = \frac{\partial \Pi}{\partial \Pi^*_{ijk}} \cdot \frac{\partial \Pi^*_{ijk}}{\partial \bar{W}_{gw}} \tag{22}$$

The signs of (21) and (22) are also mathematically indeterminate in sign since $\frac{\partial \Pi^*_{ijk}}{\partial pw}$ and $\frac{\partial \Pi^*_{ijk}}{\partial \bar{W}_{gw}}$ appear in (21) and (22) respectively.

And the signs of $\frac{\partial \Pi^*_{ijk}}{\partial pw}$ and $\frac{\partial \Pi^*_{ijk}}{\partial \overline{W}_{gw}}$ were mathematically indeterminate in sign above. In terms of economics, however, the marginal district profit function will shift inward to the extent that the marginal profit functions for each crop-soil-technology activity shift inward as in Figure 2. The shadow price effect of adoption of new technology may offset some of the decrease in marginal district profits as shown by the dotted line in Figure 2.

In summary, the theoretical structure of this model is incorporated into an actual optimization model in Chapter 4. The model introduced in Chapter 4 is used to generate empirical results on the effects of the proposed pump tax and water duty policies of the 1980 AGWMA in eight irrigation districts in the PAMA. The empirical analysis is repeated for discrete points in time. The theoretical model presented here is a simplification of the optimization model in Chapter 4. However, the most important restraints from the optimization model in Chapter 4 have been incorporated into the theoretical model presented in this chapter. The results of the empirical analysis are presented in Chapter 5.

CHAPTER 3

DESCRIPTION OF DATA USED IN THIS STUDY

The data used in this study can be divided into two groups: physical or technical data and economic data. Included in the first grouping are data such as the number of acres of different soil types in each subarea (district), types of crops and their associated yields for each soil type, water application rates for each crop, and characteristics of different irrigation technologies. The second grouping includes production costs for different crops, commodity prices, and investment costs for irrigation technologies.

Soil Classification

Eight soil classes were identified for this study. These eight soil classes were defined according to permeability; that is, how rapidly does water soak into and infiltrate through the soil. The classification system used in this study closely follows the classification used in soil survey books for Maricopa County (Maricopa County Central Part, and Eastern Maricopa and Northern Pinal County, Soil Survey Books, Soil Conservation Service, United States Department of Agriculture). The difference in classifications lies in the fact that one or more soils of the same permeability were grouped together in this study. Professor D. Post concurred with the soil classification used in this study (Post, 1982). Table 4 displays the soil classification scheme.

The number of acres of each soil class, in each district, were estimated using soil maps included in the soil survey books. After the boundaries of each irrigation district had been traced on the soil maps, the number of acres of each soil was measured using a digital planimeter.

Crops, Yields, Water Requirements

Ten crops were included in this study. The crops include alfalfa, Upland cotton, Pima cotton, barley, wheat, grain sorghum, sugar beets, safflower, spring lettuce, and fall lettuce. Since not every crop was adaptable to each soil class, A. Halderman was consulted to insure that crops and soils were correctly matched together (Halderman, 1982). Yields were obtained for each crop, within a particular soil class, using the estimated yields found in the soil survey books for Maricopa County. The yields assume a high level of management on the part of the farmer so, consequently, this assumption was implicitly incorporated into this study.

In order to attain maximum growth and yield, each crop requires a precise number of acre-inches of water per acre given a particular soil type, climate, and level of and variety of fertilizer. The precise number of acre-inches of water needed for maximum growth is called the consumptive water use of a crop. Some

TABLE 4

SOIL CLASSIFICATION USED IN THE STUDY

Classification	Rate of Permeability	Texture of Soil	Most Suitable Irrigation Technology To Be Used To Obtain Maximum Efficiency
01	Moderate to moderately slow	Clay loam throughout	Level to uniform grade with basin irrigation; most suitable technologies, regular surface, laser level surface, linear move sprinkler, and drip.
02	Moderate to moderately slow	Sandy loam underlying layer of clay loam	Level to uniform grade with short runs; most suitable technologies, regular surface, linear move sprinkler, laser level surface, and drip
03	Moderately rapid	Sandy loam	Level to a flat grade; most suitable technologies, regular surface, center pivot sprinkler, linear move sprinkler, laser level surface, and drip
04	Moderately rapid to slow	Sandy loam to clay loam	Same as 03, except center pivot and linear move sprinkler not used
05	Rapid to moderately rapid	Sandy loam underlying layer of sand	Level to a uniform grade; most suitable technologies, regular surface, center pivot sprinkler, linear move sprinkler, and drip
06	Slow to moderate	Sandy loam underlying layer of clay or clay loam	Level to a uniform grade; most suitable technologies, regular surface, laser level surface, and drip

(continued)

TABLE 4 (continued)

Classification	Rate of Permeability	Texture of Soil	Most Suitable Irrigation Technology To Be Used to Obtain Maximum Efficiency
07	Rapid	Loamy sand underlying layer of gravelly sand to sand	Level to uniform grade; most suitable technologies, regular surface, center pivot sprinkler, linear move sprinkler, laser level surface, and drip
08	Slow	Clay	Level to uniform grade; most suitable technologies, regular surface center pivot sprinkler, linear move sprinkler, laser level surface, and drip

Source: Soil Survey of Maricopa County, Arizona, Central Part, Soil Conservation Service, USDA. Classification of soil modified by author and P. Livingston.

researchers define consumptive water use as ". . . [water] . . . withdrawn from a river or groundwater aquifer and evaporated or transpired by a crop" (Kruse and Heermann, 1977). Consumptive water use is calculated as follows:

$$W_{CU} = W_{APP} \cdot WAE \qquad (1)$$

where,

W_{CU} = water needed to satisfy the consumptive water use of a crop

W_{APP} = water actually applied to a crop

WAE = water application efficiency measured as a percent.

Equation (1) can be rewritten to give:

$$\frac{W_{CU}}{W_{APP}} = WAE \qquad (2)$$

Equation (2) expresses water application efficiency as the ratio of consumptive water use, W_{CU}, to water actually applied to a crop, W_{APP}. Equation (2) is useful when comparing the water application efficiency of alternative irrigation technologies. The alternative irrigation technologies included in this study, and the application efficiencies associated with each technology are discussed in later sections of this chapter.

Irrigation Technologies

Several irrigation technologies are considered in this study. The technologies include regular surface flood, laser level surface, center pivot sprinkler, linear move sprinkler, and drip. Regular surface flood technology includes the practice of furrow and basin irrigation currently used in Arizona. Each technology is applicable in each district. Furthermore, each technology has been specifically designed to irrigate a specific number of acres. Table 5 provides general information pertaining to the alternative technologies (excluding regular surface flood). Each irrigation technology consists of various components which are engineered and sized to properly irrigate a specific number of acres. The components and costs of alternative irrigation technologies are shown in Table 6.

In this study, crops and soil types were determining factors whether or not a particular irrigation technology could be adopted and used. Table 7 shows the adaptability of the irrigation technologies to crops and soil types included in this study. The adaptability of the irrigation technologies to crops and soil types was developed from personal communications with A. Halderman (1982).

A simplifying assumption was made in this study concerning the effects of alternative irrigation technologies on crop yields; the assumption was that crop yields were constant for all technologies. The lack of reliable, empirical data on the effects of various technologies on crop yields necessitated making this assumption in this study. Yields varied by soil type in this study and irrigation technologies were adaptable to certain soils as shown in Table 7. There is an indirect link between irrigation technologies and yields through soil types. But no explicit effects of irrigation technologies

TABLE 5

GENERAL INFORMATION ON IRRIGATION TECHNOLOGIES INCLUDED IN THIS STUDY (EXCLUDING REGULAR SURFACE FLOOD)

	Irrigation Technology			
Information	Center Pivot Sprinkler	Linear Move Sprinkler	Laser Level Surface	Drip
Potential for use in all districts	Yes	Yes	Yes	Yes
Number of acres technology designed to irrigate	120	320	160	160
Pressurization of system, in psi	35[1]	35	---	30
Approximate pressure loss in system, in psi	6-8	6-8	---	22-23[2]
Gallons delivered per minute at pivot, in gpm	1,000	2,400	---	---
Energy consumed for pressurizing technologies to pump 1 acre-inch of water for field delivery, in kilowatt hours per acre-inch[3]	11.52	11.52	---	9.96

[1]These psi figures reflect low-pressure systems as opposed to high-pressure impact sprinkler systems of 60-70 psi.

[2]The pressurization of a drip system on M and W Farms near Coolidge, Arizona is as follows:

Point in System	PSI	Loss
Inlet side of filter station	30	12-15
Distribution side of filter station	15-18	6.5-9
Inlet of bi-wall tape	8.5-9	1.5
End of system	7-7.5	
Total Range of Loss		20-25.5
Average Loss		23

[3]Calculations derived by P. Livingston, engineer, Franzoy, Corey, and Associates, Tempe, Arizona.

Source: Dealers of irrigation technologies and components, and P. Livingston, engineer, Franzoy, Corey, and Associates, Tempe, Arizona.

TABLE 6

ALTERNATIVE IRRIGATION TECHNOLOGIES: COMPONENTS AND COSTS[1]

	Component	Cost
	Center Pivot Irrigation Technology (Designed for 120 Acres)	
1.	Trench and backfill, 1,320 feet	$ .60 per foot
2.	10 inch PVC mainline, 1,320 feet	$ 3.50 per foot
3.	4 strands No. 2 440 volt wire 2 strands 12-2 wire 1,320 feet 1½ inch PVC pipe	$ 1.50 per foot $ 1.50 per foot $ 1.50 per foot
4.	Pipe assembly and stringing wire through pipe, 1,320 feet	$ .15 per foot
5.	8 towers, aluminum and steel	$37,668.00
6.	8 440 volt, 3 phase motors and gear boxes	$ 1,664.00
7.	10 psi spray heads, 40 foot spacing 1,288 feet	$ .70 per foot
8.	gallon drops, 1,288 feet	$ 1.55 per foot
9.	16 rubber tires, lights, lightning arrestor	$ 4,295.00
10.	Installation, freight	$ 7,800.00
	Total	$62,334
	Linear Move Irrigation Technology[2] (Designed for 320 Acres)	
1.	Basic Ditch Feed	$24,778.00
2.	16 towers	$75,960.00
3.	16 440 volt, 3 phase motors and gear boxes	$ 3,328.00
4.	10 psi spray heads, 2,600 feet	$ .70 per foot
5.	gallon drops, 2,600 feet	$ 1.55 per foot
6.	32 rubber tires, lights, lightning arrestor	$ 8,622.00
7.	CAT 3208 diesel engine	$ 8,736.00
8.	Cornell 6 RV pump	$ 4,472.00
9.	20 KW diesel generator	$ 7,800.00

(continued)

TABLE 6 (continued)

Component	Cost
10. Freight, installation	$ 15,080.00
Total	$154,861.00
Drip Irrigation Technology (Designed for 160 Acres)	
1. Filter station, computer, cement slab, pipe, valves	$ 17,504.00
2. 8 inch PVC mainline and valves	$ 25,898.00
3. 6 inch, 5 inch, 4 inch, and 3 inch graduated PVC submainline, air vents, and valves	$ 19,714.00
4. Bi-wall tape 2,155,680 feet for 160 acres (approximately $400 per acre)	$ 65,000.00
5. Fertilizer injection pump hydraulic driven, stainless steel	$ 1,495.00
6. Installation (excluding bi-wall tape)	$ 29,100.00
7. Installation of bi-wall tape[3] approximately $30 per acre	$ 4,800.00
Total	$162,510.00
Laser Level Irrigation Technology [4] (Designed for 160 Acres)	
1. Check gates, $300 each for 20 acres [6]	$ 2,496.00 [5]
2. Erosion control structures $900 each for 10 acres	$ 14,976.00
3. Flume	$ 364.00
4. Laser equipment Laser command post Receiver and control box Hydraulic valve pump Hose and connections	$ 16,640.00
5. 175 HP 4WD tractor	$ 72,708.00
6. 10 foot blade scraper	$ 2,597.00
Total	$109,781

(continued)

TABLE 6 (continued)

[1]Price quotations include a 4.0 percent sales tax.

[2]Assume 2,600 foot cement ditch is already in place on the farm.

[3]Assume installation of bi-wall tape is done by farm workers as on M&W farms near Coolidge, Arizona.

[4]Assume all needed ditches already exist on the farm.

[5]These costs reflect what this author identifies as farm firm owned components of the laser level technology. It is implicitly assumed in the above costs that custom hired operations are not included. These custom hired operations and their associated costs were determined from personal communications with Allan Halderman and Charlie Robertson:

(a) Ditching at $100 per acre (approximate),
(b) Earth moving at $.50 per cubic yard for approximately 350 cubic yards per acre and for slopes greater than 0.6 percent,
(c) Chiseling at $16 per acre,
(d) Manure for soil cover and replacement of soil nutrients at $5 per ton.

[6]Components taken from the bulletin by Hinz and Halderman (1978).

Source: Dealers of irrigation systems and components.

TABLE 7

IRRIGATION TECHNOLOGY ADAPTABILITY TO CROPS AND SOIL TYPES USED IN THIS STUDY

	Irrigation Technologies				
Crops	Regular Surface Flood	Center Pivot Sprinkler	Linear Move Sprinkler	Laser Level Surface	Drip
Alfalfa	Yes	Yes	Yes	Yes	No
Upland Cotton	Yes	Yes	Yes	Yes	Yes
Pima Cotton	Yes	Yes	Yes	Yes	Yes
Barley	Yes	Yes	Yes	Yes	No
Wheat	Yes	Yes	Yes	Yes	No
Sorghum	Yes	Yes	Yes	Yes	No
Sugar Beets	Yes	Yes	Yes	Yes	No
Safflower	Yes	Yes	Yes	Yes	No
Spring Lettuce	Yes	No	No	Yes	Yes
Fall Lettuce	Yes	No	No	Yes	Yes
Soil Types					
01 - Clay loam	Yes	No	Yes	Yes	Yes
02 - Sandy loam/underlying layer of clay loam	Yes	No	Yes	Yes	Yes
03 - Sandy loam	Yes	Yes	Yes	Yes	Yes
04 - Sandy loam to clay loam	Yes	No	No	Yes	Yes
05 - Sandy loam/underlying layer of sand	Yes	Yes	Yes	No	Yes
06 - Clay surface layer	Yes	No	No	Yes	Yes
07 - Sandy loam	Yes	Yes	Yes	No	Yes
08 - Clay	Yes	Yes	Yes	Yes	Yes

Source: Personal Communication with Allan Halderman, Spring, 1982.

on yields are transferred through this soil type link and so yields are assumed constant over all irrigation technologies. The costs associated with each irrigation technology, considered in this (excluding regular surface flood) are shown in Table 8. These costs are held constant throughout each discrete time period considered in this study. It is highly probable that the cost of alternative irrigation technologies such as sprinkler, laser level, and drip could decrease over time. However, reliable estimates of such cost decreases are not currently available.

Costs of Crop Production and Commodity Prices

The costs of producing crops within an irrigation district in the PAMA were estimated using the budget system developed by Hathorn (Hathorn and Farr, 1982). Since the budget system did not include budgets for lettuce, separate budgets for spring and fall lettuce were taken from budgets developed by Aillery for the Colorado River Indian Reservation in La Paz County,[1] Arizona (Aillery, 1982).

The crop budgets were developed for a representative pump water district in Maricopa County (which encompasses the PAMA) and a representative surface water district in Maricopa County. The principal difference between the two budgets is the cost of irrigation water; irrigation water in the pump water only districts is

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1. The northern half of Yuma County became La Paz County on January 1, 1983.

TABLE 8

COSTS OF ALTERNATIVE IRRIGATION TECHNOLOGIES
(EXCLUDING REGULAR SURFACE FLOOD) INCLUDED IN THIS STUDY

	Irrigation Technology			
Cost Component	Center Pivot Sprinkler	Linear Move Sprinkler	Laser Level Surface	Drip
Investment Cost per Acre	$519.45	$ 483.94	$ 686.13	$1,015.69
Annual Fixed Costs per Acre[3]	$ 63.64	$ 60.36	$ 135.16	$ 209.99
Repairs and Maintenance				
Annual Cost	$500.00	$1,000.00	$1,413.00[1]	$3,250.00[2]
Cost per Acre/Year	$ 4.17	$ 3.12	$ 3.83	$ 20.31
Labor				
Cost per Acre/Year	$ .23[4]	$ .18[4]	$ 10.40[4]	$ 26.80

[1]In a personal communication with S. Gordin, it was learned that in his years of work with laser level technology in South America approximately 4 percent of investment cost for check gates, erosion control structures, and flumes is spent on repairs and maintenance.

[2]Assumes 2 percent of investment cost is spent on repairs and maintenance.

[3]Includes depreciation, interest, taxes, and insurance.

[4]Assumes an average of 8 irrigations per crop year for center pivot, linear move, and laser level. Annual cost was divided by the number of acres each technology was designed to irrigate: 120 acres for center pivot, 320 acres for linear move, 160 acres for laser level, and 160 acres for drip.

Source: Hinz and Halderman (1978), dealers of irrigation technologies and components, S. Gordin, personal communication, Rathwell and Leyden (1976), and Peter Livingston, personal comm.

more expensive than irrigation water in surface water districts.[2] Five separate crop budgets were developed for each crop grown in each district in the PAMA. One crop budget was developed for each irrigation technology.

Commodity prices were based on the most likely expected price for a particular commodity as found in Hathorn and Farr (1982). The prices were expressed in dollars per pound of a commodity. The price of spring and fall lettuce was chosen to be an average of the seasonal price of lettuce for the years 1977-1981 (1981 Arizona Agricultural Statistics). Product prices were assumed constant over time.

Total variable costs of production were calculated using the pump water and surface water crop budgets of Hathorn (Hathorn and Farr, 1982). The variable costs for surface water and groundwater were separated from the other variable costs of crop production. The water costs play a vital role in the linear programming models of this study, since the proposed pump tax policy of the 1980 AGWMA will impact upon these costs.

Irrigation district water prices were updated from the 1982 Maricopa County Field Crop budgets of Hathorn and Farr (1982) through personal communication with officials of individual districts in the PAMA (Grady, 1982; Ward, 1982; Conovaloss, 1982; Yancy,

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2. Irrigation water may originate from groundwater or surface sources in a surface water district. All water in these districts is delivered to farms via district-owned surface distribution systems.

1982; Alexander, 1982). Table 1 above shows the costs for irrigation water in each district in PAMA considered in this study.

Water Application Efficiencies of Alternative Irrigation Technologies

Water application efficiency varies between technologies. Water application efficiency has been defined by the American Society of Civic Engineers as "the ratio of the average depth of irrigation water stored in the root zone to the average depth of water applied. The water stored in the root zone presumably is available for consumptive use by the crop" (Kruse and Heermann, 1977). For example, if a particular crop requires an average depth of water stored in the root zone of 40 inches and the average depth of water applied is 50 inches, the water application efficiency is 80 percent.

Water application efficiencies are important, but can vary from field to field depending on ". . . the degree to which system design considers climate, soil, crop, and topography" (Kruse and Heermann, 1977, p. 266). In this study, the water application efficiency of any particular irrigation technology is assumed constant over all soil types. However, as noted above, yield varies by soil type and, since irrigation technology adaptability varies with soil type, the water use efficiency of each irrigation technology also varies implicitly with yields. In Table 9, the estimated number of acres of each soil type, the grand total of all acres, and the percent of the total acres comprised of each soil

TABLE 9

ESTIMATED NUMBER OF ACRES OF EACH SOIL TYPE, THE TOTAL OF ALL ACRES, AND THE PERCENT OF THE TOTAL ACRES COMPRISED OF EACH SOIL TYPE FOR THE PAMA, 1982, AND WATER HOLDING CAPACITY FOR EACH SOIL TYPE

Area	Soil Type							
	01	02	03	04	05	06	07	08
Salt River Project	61,484	15,825	18,677	----	5,534	--	2,667	---
Buckeye Irrigation District	13,498	50	2,033	----	958	23	179	1,289
Maricopa County Municipal Water Conservation District	11,716	2,487	4,880	----	3,778	--	21	---
Roosevelt Irrigation District	15,917	7,287	8,340	----	1,801	--	155	---
Roosevelt Water Conservation District	24,655	2,643	1,003	5,512	-----	--	3,168	---
Queen Creek Irrigation District	17,160	3,300	-----	----	1,320	--	-----	---
Tonopah Irrigation District	8,450	1,806	3,081	----	1,665	--	1,146	---
McMicken Irrigation District	24,010	3,866	4,489	----	1,517	--	91	---
Total	176,890	37,264	42,473	5,512	16,573	23	7,429	---
Grand Total - All Acres = 287,453								
Percent of Total Acres Comprised of Each Soil Type	62%	13%	15%	2%	6%	0%	2%	Approx. 0%
Water Holding Capacity of Each Soil Type, in inches	6-13.5	8-12	5-7	5-12	4-7	3-10	2-5	9-10

Source: Estimated acreage figures from soil maps, and soil survey of Maricopa County, Arizona, Central Part.

type is shown for the PAMA in 1982. The soil types 01 to 98 are defined in Table 4 above. The water holding capacity of each soil type is also shown. As can be seen in the last row in the table roughly 75 percent of the soil in the PAMA has similar water holding capacities. Because the water holding capacities are similar over the majority of the soil in the PAMA, water application efficiencies will be similar over these soils. Therefore, the assumption of constant water application efficiencies for the alternative irrigation technologies considered in this study is a reasonable assumption for the majority of soil in the PAMA.

The water application efficiencies for each irrigation technology were based on the careful evaluation of the important factors affecting water application efficiency made by A. Halderman (1982). The five irrigation technologies in this study were rated for average water application efficiency as follows: regular surface flood, 65 percent; center pivot sprinkler and linear move sprinkler, 80 percent; laser level surface, 90 percent; and drip, 85 percent (Halderman, 1982).

The water savings associated with each technology for a particular crop is explicitly incorporated in this study. By rewriting equation (1) above, we read,

$$W_{APP} = \frac{W_{CU}}{WAE} \qquad [(2) \text{ repeated})]$$

the amount of water, W_{APP} needed to produce one acre of a crop can be calculated. An irrigation technology with a higher application efficiency, WAE, will require less water to produce one acre of a crop, or W_{APP}. The resulting water savings is reflected in this study to be a lower amount of water applied to a crop.

Capital Availability for Investment in Alternative Irrigation Technologies

The extent of investment in alternative irrigation technologies in this study is limited by the investment cost per acre for a technology and the amount of capital available. The per acre investment cost for each alternative technology are shown in Table 8 above.

The amount of total available capital for investment in Maricopa County was determined from loans made by the Farmers' Home Administration (FMHA) in Maricopa County in the summer of 1982. These loans were used in lieu of loans made to Maricopa County farmers by the state's three largest banks, since the desired data on loans to Maricopa County farmers was unavailable. The total amount of loans made for operating purposes, soil, and water development, and irrigation and drainage development were added together and the total amount of over $6.5 million, was then used as the amount of capital available in each irrigation district in this study. It was assumed in this study that the loans made in these categories could be used for investment in new irrigation technologies.

An interest rate of 7.3 percent was used in calculating interest costs on investment in this study. The 7.3 percent rate equals the average interest rate charged by commercial banks for loans from the years 1976 to 1982 (based on Chase Econometrics, RDA data, 1982).

CHAPTER 4

THE METHOD OF ANALYSIS

In order to analyze the possible effects of the proposed pump tax and water duty of the 1980 AGWMA on agriculture in the PAMA, representative recursive linear programming models, or RLPM, were developed for each district in this study. The representative RLPM were developed to represent the situation of farmers in the eight irrigation districts in the PAMA included in this study.

The RLPM models incorporate the usual components of a linear programming model; namely, a linear objective function, linear resource constraints and non-negativity requirements. In addition, a RLPM is characterized by the feature of flexibility restraints. The flexibility restraints limit the year-to-year changes in crop production levels.

The RLPM's developed for each irrigation district in this study are solved for three discrete time periods; a "base" period, the year 1990 and the year 2000. The flexibility constraints connect changes in the number of cropped acres produced in each irrigation district in the PAMA in the "base," the year 1990, and the year 2000. Thus, the effects of past cropping decisions are carried forward to influence present cropping decisions in this study.

Figure 3 illustrates the linkage between current and future cropping decisions through the use of flexibility constraints.

Determination of Flexibility Coefficients

Flexibility coefficients can be estimated using several procedures (see Schaller, 1964). The method of estimation of flexibility coefficients chosen in this study can be found in Miller (1972). Using this method, the estimated flexibility coefficient, β, is:

$$\beta = \frac{S}{\overline{Y}} \qquad (1)$$

where,

S = sample standard deviation of a crop acreage in a district

$\overline{Y}$ = sample mean of a crop acreage in a district.

The estimated flexibility coefficient in (1) is analogous to the coefficient of variation. The coefficient of variation provides a measure of the relative variation within a sample of data, and it is independent of any units. In this study, (1) provides a measure of the spread or variation in the distribution of the acres of a particular crop about the average or mean number of acres for the crop.

The formula for estimating β in (1) was chosen for ". . . its statistical simplicity and . . . relatively accurate predictions" (Miller, 1972, p. 71). According to Miller (1972) two basic components comprise the flexibility constraints in (1); the first is a

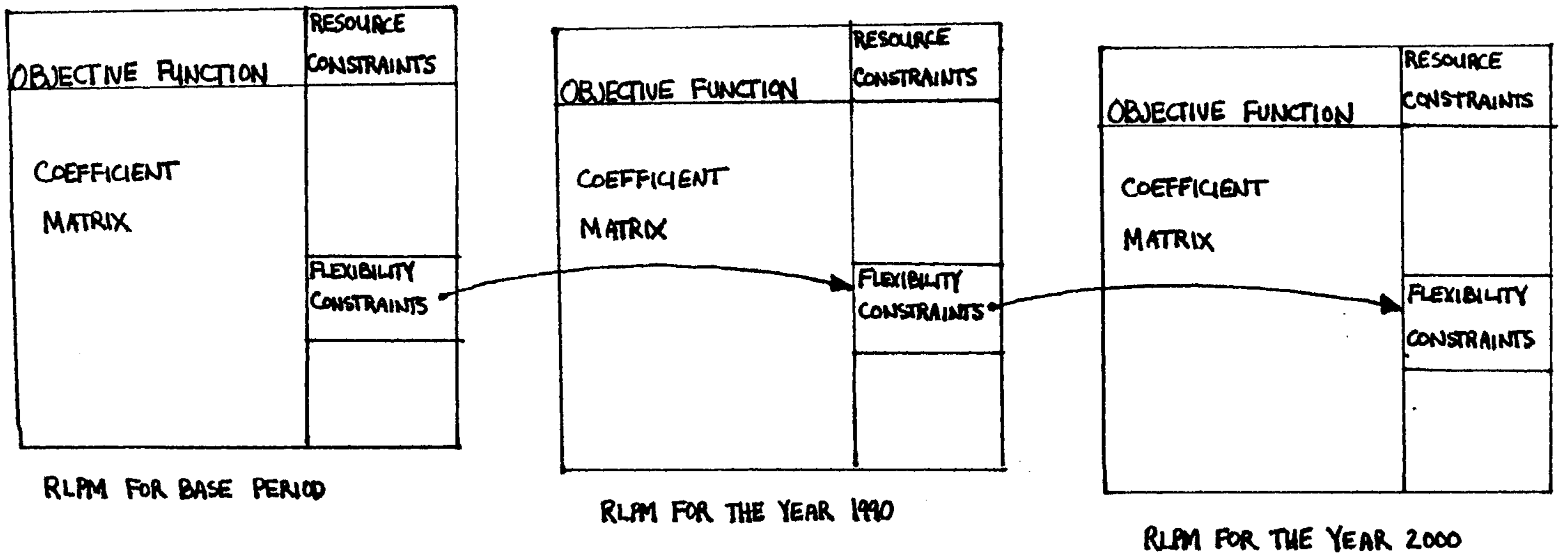

Fig. 3. Illustration of the Linkage Between Current Cropping Decisions and Future Cropping Decisions Through Flexibility Constraints.

base, which is $\bar{Y}$ in (1), and the second is the flexibility coefficient, which is β in (1) above. The method used to determine either of these components affects the total expected error of the RLPM.

The number of acres of a crop existing in a given year, or Y_n, was compared to the base in (1), or $\bar{Y}$, which is the mean, of a historical acreage series. Flexibility restraints were then calculated with this new base and the total expected error associated with this new base was computed. Miller concluded that "none of the flexibility restraints using the current year, Y_n, as the base results in estimates more accurate than using the mean $\bar{Y}$ . . . simply using $\bar{Y}$. . . results in lower total expected error than any RP model procedure using Y_n as the base for the flexibility restraints" (Miller, 1972, p. 76).

Similarly, alternative flexibility coefficients were compared to β in (1) above. The alternative flexibility coefficients were defined as:

$$\bar{\beta} = \frac{\sum_{i}^{\bar{n}} \frac{Y_i - Y_{i-1}}{Y_i}}{\bar{n}} \qquad \text{for all } Y_i > Y_{i-1}$$

and, (2)

$$\underline{\beta} = \frac{\sum_{i}^{\underline{n}} \frac{Y_i - Y_{i-1}}{Y_i}}{\underline{n}} \qquad \text{for all } Y_i < Y_{i-1}$$

where,

$\overline{n}$ = number of years in which crop acreage increased

$\underline{n}$ = number of years in which crop acreage decreased

Y_i = acreage of a crop in year i

Y_{i-1} = acreage of a crop in year i-1

According to Miller ". . . using the flexibility coefficients $\overline{\beta}$ and $\underline{\beta}$ [in 2] results in an even larger bias . . . than does use of the coefficient of variation [β in (1)] . . ." (Miller, 1972, p. 74). On the basis of these results, equation (1) was chosen as a reasonable method of estimating the flexibility coefficients for each irrigation district in the PAMA included in this study.

The flexibility coefficients used in this study were calculated from district records and engineering reports (Irrigation District Offices, W.S. Gookin and Associates, and Franzoy, Corey, and Associates, all 1982). Sample means and sample standard deviations were calculated for each crop. The flexibility coefficients, the β's, were computed from (1). The flexibility coefficients estimated for each crop in the districts included in this study are shown in Table 10.

The flexibility coefficients in Table 10 were incorporated into the following upper and lower flexibility restraints:

$$\text{Upper Bound} = \overline{Y}(1+\beta)$$

$$\text{Lower Bound} = \overline{Y}(1-\beta) \qquad (3)$$

where

β = is the flexibility coefficient computed in (1).

TABLE 10

ESTIMATED FLEXIBILITY COEFFICIENTS BY CROP AND DISTRICT

	Alfalfa	Upland Cotton	Pima Cotton	Wheat	Barley	Sorghum	Safflower	Sugar Beets	Spring Lettuce	Fall Lettuce
	------------------	------------------	------------------	------------------	------------------	Percent	------------------	------------------	------------------	------------------
Salt River Project	.37	.29	.07	.73	.95	.67	.69	.18	.71	.60
Buckeye Irrigation District	.17	.59		.58	.92	.70				
Maricopa County Municipal Water Conservation District		.14			.56				.92	.44
Roosevelt Irrigation District	.38	.33	.07	.59	.51		.53	.33		
Roosevelt Water Conservation District	.18	.33	.07	.89	.46	.01		.53	.77	.77
Queen Creek Irrigation Dist.		.31	.07	.81		.34				
Tonopah Irrigation District	.27	.35		.58	.66					
McMicken Irrigation District		.35		.58	.66			.33	.14	.14

Source: Author's calculations from irrigation district records and engineering reports.

"The flexibility restraints are simply upper and lower bounds on the allowable year-to-year change in . . . the acreage of each crop in the model. Their role is to account for the many forces causing lags in adjustment [by farmers] . . ." (Schaller and Dean, 1965, p. 7).

The flexibility constraints perform the role of linking past and present cropping decisions. In this study three discrete time periods are considered: the "base," the year 1990, and the year 2000. The upper and lower flexibility constraints connect the past and present in this study in the following manner:

the "base" - Upper Bound = $\overline{Y}(1+\beta)$

Lower Bound = $\overline{Y}(1-\beta)$

where,

$\overline{Y}$ = sample mean of the historical crop acreage series for each crop in each district

β = flexibility coefficient computed in (1) above

the year 1990 - Upper Bound = $Y^{base}(1+\beta)$

Lower Bound = $Y^{base}(1-\beta)$

where,

Y^{base} = number of acres of each crop chosen in the RLPM solution for the "base" time period.

the year 2000 - Upper Bound = $Y^{1990}(1+\beta)$

Lower Bound = $Y^{1990}(1-\beta)$

where

Y^{1990} = number of acreas of each crop chosen in the RLPM solution for the year 1990.

Detailed series on crop acreages were not available for the pump water only districts of Queen Creek, Tonopah, and McMicken. Data on crop acreages were not available, because these districts do not maintain offices as do the other districts even though farmers in each district elect officers. The members (farmers) of these districts pump water from private wells and have not maintained records on groundwater pumpage and cropped acres. Flexibility coefficients for Queen Creek Irrigation District (QCID) were calculated as the average of crop acreage in the Salt River Project (SRP) and Roosevelt Water Conservation District (RWCD). Since QCID lies adjacent to RWCD and near SRP land, it was assumed that an average value for the flexibility coefficients would reasonably represent QCID.

Similarly, an average of Buckeye Irrigation District (BID), Roosevelt Irrigation District (RID), and Maricopa County Municipal Water Conservation District (MCMWCD) flexibility coefficients were used for Tonopah Irrigation District (TID) and McMicken Irrigation District (MID). Since TID and MID are geographically close to BID, RID, and MCMWCD, it was assumed that average values for the flexibility coefficients of BID, RID, and MCMWCD, were reasonable estimates for TID and MID.

The same soil types are present in TID and MID as in BID, RID, and MCMWCD. Therefore, it can be assumed that the calculated average flexibility coefficients in TID and MID reflect the same soil-yield effects as in BID, RID, and MCMWCD. Also, the same soil types are present in QCID as in SRP and RWCD and so it can be assumed that the average flexibility coefficients in QCID reflect the same soil-yield effects as in SRP and RWCD.

The estimated flexibility coefficients for spring and fall lettuce in MID do not equal the flexibility coefficients for lettuce in MCMWCD. According to a W.S. Gookin and Associates engineer (W. Scutter, 1982), a study conducted by the company in the early 1970s indicated that spring and fall lettuce comprised 14 percent of the crop acreage in MID. Therefore, in this study spring and fall lettuce were given a flexibility coefficient of 14 percent for MID.

An acreage limitation is usually placed upon Pima cotton to prevent an all-cotton solution in the models. Therefore, a restriction on the number of acres of Pima cotton that can be grown was formulated for the districts in which Pima cotton was produced. It was learned from the USDA Agricultural Marketing Service Cotton Division (1982) that approximately 251,250 acreas of cotton were grown in Maricopa County in 1981. The Maricopa County allotment for Pima cotton was about 17,771 acreas or 7 percent of all cotton acreage. Therefore, for each district in the PAMA which produced Pima cotton, a maximum of 7 percent was used as a flexibility coefficient for Pima cotton.

Explanation of the Recursive Linear Programming Model Used in This Study

The recursive linear programming models (RLPM) used in this study maximizes a linear objective function subject to linear constraints. The objective function to be maximized is net returns above the variable costs of production. As the proposed pump tax and water duty policies of the 1980 AGWMA are enacted net revenues, cropped acreas, water and energy use, and investment in irrigation technologies in each district in the PAMA will be impacted.

RLPM are developed for each irrigation district in the PAMA. The models are basically similar but are differentiated on the basis of whether a district is a surface and pump water area or a pump water area only. The different identified soil types are included in the crop production activities of the districts. A particular crop is identified as being capable of growing on a particular soil. Each irrigation technology that is compatible to a particular soil is then identified. Therefore, a crop production activity in a district is defined in the model as the production of a particular crop on a particular soil using one of the appropriate technologies.

The recursive models in this study represent the crop production activity of all farms (except citrus) within a district in the PAMA. The results of the 8 irrigation district models are aggregated to obtain regional impacts in the PAMA resulting from the enactment of the proposed pump tax and water duty policies of the 1980 AGWMA.

The objective function of each model maximizes the net revenues accruing to a district minus the total variable costs of crop production. The total variable costs of crop production consist of four principal components in the models: per acre cost of crop production minus water costs, costs of groundwater and/or surface water, irrigation technology investment costs, and the cost of electric energy for pumping and irrigation system pressurization. The total variable costs of crop production are subtracted from the total revenue which results from selling each crop commodity at the prevailing market price. Figure 4 presents a simple schematic diagram of the important components of each RLPM developed for each district included in this study. A more detailed description of the RLPM objective function and constraints follows.

Description of the Recursive Linear Model Objective Function and Constraints

The Objective Function

The objective function of the RLPM model used in this study maximizes the net returns above variable costs of production. The net returns for each individual model reflect the returns of all the farm firms within an irrigation district. The net returns from all the districts are summed to determine net returns to the PAMA.

OBJECTIVE FUNCTION

Crop Production Activities	Water "Buying" Activities Pump Water and/or Surface Water	Energy "Buying" Activity	Irrigation Technology Investment Activities	Commodity "Selling" Activities	Model Restraints
					Land Restraint by Soil Type
					Water Availability Restraint Groundwater and Surface Water
					Upper and Lower Crop Acreage Flexibility Restraints Links Past and Present Cropping Decisions
					Capital Availability Restraint For Investment in Alternative Irrigation Technologies

Fig. 4. Schematic Diagram of RLPM Developed for Each District in the PAMA Included In This Study.

Total revenue accrues from the sale of commodities. The market prices offered for the commodities that are produced are assumed to be constant throughout all time periods.

Costs consist of several components. The costs of producing an acre of a crop on a particular soil type with a particular irrigation technology times the number of acres of each crop produced comprise the per acre production costs of the model. The cost of groundwater and surface water are removed from the per acre production costs. These water costs form their own cost component. It is particularly efficacious to separate out water costs from total per acre production costs, since the proposed pump tax of the 1980 AGWMA impacts directly upon the cost of groundwater either supplied to farms by the district itself or pumped directly by private farm wells. Thus, this cost component can be changed easily to reflect the proposed pump tax policy of the 1980 AGWMA. It should be noted that only the cost of an acre-foot of groundwater supplies increases. While the cost of surface water may rise throughout the study period, it is assumed for the purposes of this study that the cost of an acre-foot of surface water remains constant.

Connected to groundwater use is energy consumption for pumping. The energy cost can reflect either the cost to the district, if district-owned wells provide the water, or the cost to a private farm if farm-owned wells provide the water. Once again the cost per kilowatt-hour charged by the Salt River Project and

Arizona Public Service Company for irrigation is assumed to remain constant throughout the study period.

An additional cost for energy is levied per kilowatt-hour consumed for pressurization of irrigation technologies. Center pivot, linear move, and drip irrigation technologies require energy to force water through the system and then out through either sprinkler nozzles or bubblers to the crop. The cost for pressurizing the systems is incurred regardless of whether groundwater or surface water supplies are used for irrigation. This cost, while reflecting an additional energy cost resulting from the consumption of water supplies, also reflects a cost for an alternative irrigation technology over and above the per acre investment cost for the technology.

The cost for each alternative irrigation technology enters the objective function as the per acre service cost for each alternative technology. This per acre cost is composed of four components; the depreciation, interest, taxes, and insurance costs incurred for each technology.

These costs are normally considered to be fixed. This is true once the investment has been made, but these costs are variable when the farmer is contemplating whether or not to invest in a new irrigation technology.

Therefore, the variable costs associated with investment in additional acres of some technology are included in the objective function. Once again these costs are variable because the farmer has not yet made the investment, but instead is assumed to decide between investing or not investing in an irrigation technology. The objective function includes the service cost to existing acres of each technology in each district. The service cost is set at zero in the objective function because the costs incurred on these acres is fixed, and only variable costs are considered in the objective function. However, these fixed costs would be subtracted from net revenue in order to determine the short-run and long-run profitability of the farm firm.

The primary function of this investment activity is to insure that the existing number of acres of each technology in each district are included in the feasible solution of the models. It is assumed therefore, that no fewer than the existing acres of each technology will be used in each district. In other words, a certain number of acres of each technology in an irrigation district in the PAMA are "inherited" from investment decisions made in preceding time periods. The acres in each district which are not irrigated by laser level surface, sprinkler, or drip technologies are irrigated with regular furrow or flood surface technologies.

The "inherited" number of acres of each technology in a district provides a base which can be augmented through further investment. In order to calculate an "inherited" number of acres of each technology in each district required an estimate of cropped acreage in Maricopa County. Crop acreage in Maricopa County was 477,850 acres in 1978 (Arizona Statistical Review, 1979).

Approximately 20,000 acres of laser level surface, 15,000 acres of center pivot sprinkler, 800 acres of linear move sprinkler, and 45 acres of drip were estimated to exist in Maricopa County in 1982 (Walt Parsons, Arizona Department of Water Resources, 1982). The percent of total county acres in each irrigation district was computed to serve as a weight to divide the acres of technology between the 8 districts in the PAMA. The percentage weights computed for each irrigation district in the PAMA are as follows: SRP, 22 percent; BID, 4 percent; MCMWCD, 5 percent; RID, 7 percent; RWCD, 8 percent; QCID, 8 percent; TID, 3 percent; and MID, 7 percent. In the SRP, for example, 22 percent of the 20,000 acreas of laser level, 1,500 acres of center pivot, 800 acres for linear move, and 45 acres of drip was calculated to give an estimated 4,400 acres of laser level, 330 acres of center pivot, 176 acres of linear move, and 9.9 acres of drip "inherited" from the past. Similar computations were performed for the other 7 irrigation districts.

The Constraints

The Land Constraint

The land constraint limits the number of acres of each soil type found within a district to the number of acres determined from the soil survey books for Maricopa County (Soil Survey of Maricopa County, Central Part, and Soil Survey of Eastern Maricopa County and Northern Pinal County). Specifically, the constraint indicates that the total number of acres of a certain soil type used to produce a crop with a particular irrigation technology cannot exceed the total number of acres of that soil type found in a district.

The Commodity Balance Row

This row performs an accounting function within the model. It insures that the total output of each commodity produced is actually sold. Therefore, there is no shortage or excess of output of any commodity in the model.

The Water Balance Row

This row accounts for the total amount of water supplies used for crop production. All quantities of groundwater and surface water supplies required to produce an acre of a particular crop on a particular soil type with a particular irrigation technology in any one of twelve time periods (months) are added together. The total amount required is then supplied within the model. Once again it is the case that no shortage or excess amounts of water occur in the production of an acre of any crop.

The Pump Water Constraint

This constraint restricts the total amount of groundwater that can be pumped in any month of a crop year to produce a crop on a particular soil type with any irrigation technology.

Total quantities of groundwater available for pumping in any one month were determined from analysis of irrigation district pumping practices. While each district will adapt its pumping to specific external factors such as extreme rainfall or drought in any one year, a general pattern seemed to underlie the basic pumping practices of the districts. The basic pumping practice that emerged was simply that district wells operated longer, and more water was pumped in the summer months than in any other portion of a year. Further, pumping in the "fall" or "spring" months exceeded that in the winter months.

Therefore, the pumping pattern decided upon and assumed to reasonably represent general district pumping practices was the following: Low use months consisted of January, February, November, and December; moderate use months consisted of March, April, September, and October; and high use months consisted of May, June, July, and August.

Using district pumping records, the total number of hours that a typical well would operate each day in the low, moderate, and high use periods was estimated. Multiplying the total amount of time the wells were used in each use period by the average pumping capacity of the wells gave the total number of acre-feet available for pumping in each four month use period. The total was divided by four which distributed the total number of acre-feet pumped equally between each month in a particular use period.

Estimating the number of acre-feet pumped in each use period was relatively straightforward for the organized irrigation districts which have maintained orderly records of previous pumping. The pump water-only districts of Queen Creek, Tonopah, and McMicken had no orderly system of records. The pumps, being privately owned, had not been monitored closely in the past. Rough estimates of previous pumping levels were obtained from the engineering firms of Franzoy, Corey, and Associates (1982) W.S. Gookin and Associates (1982) and from Walt Parsons (1982) of the Department of Water Resources. Using these best estimates, the total number of acre-feet available for pumping in these districts for a particular time period was estimated.

The Surface Water Constraint

This constraint limits the amount of surface water available for irrigation in any one month. Once again district records were used to estimate these constraints. The surface water districts provided complete surface water usage in acre-feet by month for several prior years. Therefore, an average amount of available water supplies was calculated from these histories provided by each surface water district.

The Energy Balance Row

This row accounts for the total amount of energy consumed in pumping groundwater supplies. The total amount of energy required to pump the total number of units (acre-inches) of groundwater is the amount that is consumed within the model.

The Pima Cotton Acreage Constraint

This constraint averts an all-cotton crop mix within the model. Pima cotton typically enjoys a higher price than the short-staple Upland cotton variety. Thus, without a constraint the model would tend to choose to produce all the Pima cotton that it could given the constraints of land and water.

The Acreage Flexibility Constraints

These constraints furnish upper and lower bounds on cropped acreage. As explained below, the flexibility coefficient, β, is calculated as the sample coefficient of variation, $\beta = \frac{S}{\overline{Y}}$. Incorporating this coefficient into the upper and lower flexibility constraint limits, the percentage increase or percentage decrease in the cropped acres of a crop in the current time period relative to the number of acres of this crop in the previous time period is $Y^{\text{previous period}}(1+\beta)$ and $Y^{\text{previous period}}(1-\beta)$ respectively.

The Irrigation Pressurization Balance Row

This row insures that the amount of energy required to pressurize center pivot, linear move, and drip technologies in order to properly apply irrigation water will be provided within the model.

For example, the total number of acre-inches pumped throughout a twelve month period on a particular crop is summed and then is multiplied by the required number of kilowatt hours per acre-inch needed to pressurize the system for irrigation.

The Service to Capital Balance Row

This row balances the amount of capital needed to cover the service costs of capital including depreciation, taxes, insurance, and interest charges. These service costs are calculated on a per acre basis. Each acre of a new irrigation technology will have an associated cost attached to it.

If any acres of a technology exist within a subarea at the beginning of a time period, these service costs are actually fixed and do not enter the objective function (the objective function coefficients are zero). Only if additional investment in an alternative technology occurs will these costs enter the objective function, for at this stage, they can still be considered variable costs associated with investment in additional acres of an irrigation technology.

The Upper Bound on Existing Acres of a Particular Technology Constraint

In 1982, a certain number of acres of each alternative technology considered in this study existed in Maricopa County. In order to account for these pre-existing acres a method was used to allocate these acres among each subarea based upon the total number of cropped acres in each district relative to the total number of cropped acres within Maricopa County.

The estimated total of each technology existing within Maricopa County was determined to be 20,000 acres of laser level surface, 1,500 acres of center pivot, 800 acres of linear move, and

45 acres of drip (Parsons, 1982). These estimates are probably the most reliable available in lieu of an extensive district-by-district survey of the entire county.

Total cropped acreage in Maricopa County was determined from the 1979 Arizona Statistical Review. The number of cropped acres in each district, as found in DeCook, et al., (1978) was used to determine the percentage of total county acres in each district. These percentages were then used to determine the acres of each technology found in each irrigation district.

The constraint requires that the number of acres of each technology "inherited" from prior periods in each district enter the feasible solution of each model solution.

The Investment Capital Availability Constraint

This constraint places a limit on the amount of capital available for investment in irrigation technology. Two investment scenarios were considered in this study: (1) the available capital was set at an amount equivalent to the outstanding loans made to farmers by the Farmers' Home Administration in Maricopa County as of August, 1982, and (2) all available capital needed for investment was assumed to be forthcoming. These two scenarios provided polar cases of investment activity.

The Model Alternatives and Investment Scenarios

The models for each district included in this study are solved for the "base" time period. The models are then resolved for the year 1990 and for the year 2000. These runs do not include the imposition of the proposed pump tax and water duty policies of the 1980 AGWMA. The only changes in these models result from the changing flexibility constraints as explained above. In order to compare and contrast the effects of the proposed policies of the 1980 AGWMA, the models are resolved for the year 1990 and for the year 2000 incorporating the proposed pump tax policy. Similarly, the models are resolved for the year 1990 and the year 2000 for the water duty policy. Therefore, for each irrigation district in the PAMA included in this study the following solutions are generated: a "base" solution; a 1990 and a 2000 solution without the proposed policies of the 1980 AGWMA; a 1990 and a 2000 solution with the pump tax policy; and, a 1990 and a 2000 solution with the water duty policy.

The effects of an investment constraint on capital versus no investment constraint on capital provides two investment scenarios for each model. The investment constraint and no investment constraint scenarios are explained above. In total, each model is solved separately 7 times for the "with investment constraint" scenario and then is solved another 7 times for the "without investment constraint" scenario. Figure 5 illustrates the alternative model solutions for each investment scenario. The empirical results of the model solution runs are presented in the following chapter. The mathematical model used in this study is presented in Appendix C.

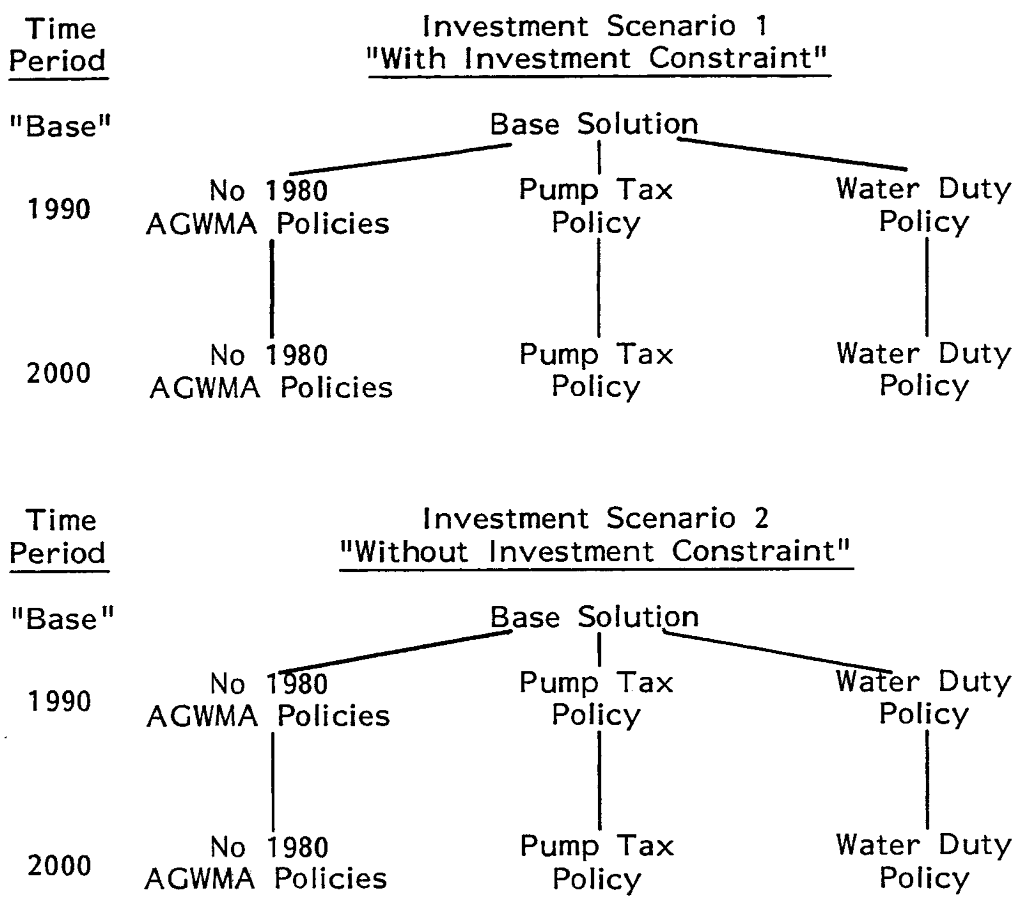

Fig. 5. Diagram of RLPM Model Solution Runs

CHAPTER 5

RESULTS OF THE MODEL ANALYSES

The results of the RLPM analyses for the two alternative investment scenarios are presented in this chapter. The model results in both investment scenarios compare and contrast the effects of the proposed pump tax policy and water duty policy of the 1980 AGWMA relative to the situation when neither proposed policy is in force. The regional (PAMA) solution results, which comprise the aggregated district results, are presented in Tables 11-15.

Regional (PAMA) Model Results

When investment is constrained, net revenues in the region decline 2.7 percent due to the proposed pump tax and decline 10.1 percent under the proposed water duty policy in the year 1990, as compared to regional net revenues when no AGWMA policies are enacted. In the year 2000, net revenues show a decline of 6.3 percent and 24.5 percent under the proposed pump tax and water duty policies respectively. These results are shown in Table 11. In the unconstrained investment case, net revenues decline 3.8 percent and 11.3 percent under the pump tax and water duty policies, respectively, in the year 1990, when compared to the net revenues which result when no policies are enacted. In the year 2000, for the unconstrained case, net revenues decrease 5.8 percent under the proposed pump tax and 24.0 percent under the proposed water duty when compared to the case with no AGWMA policies. These results are also shown in Table 11.

The results in Table 12 show that, on a regional level, groundwater use decreases on a percentage basis under both investment scenarios.

For the year 1990, in the constrained investment case, groundwater use decreases 2.2 percent and 28.0 percent under the proposed pump tax and water duty respectively. Groundwater use declines 3.8 percent and 65.3 percent, respectively, under the proposed pump tax and water duty policies in the year 2000, when compared to groundwater use with no AGWMA policies enacted.

When investment is unconstrained groundwater use decreases 1.3 percent under the proposed pump tax policy and 27.4 under the proposed water duty policy in the year 1990. Groundwater use shows a 2.2 percent decrease and a 64.1 percent decrease, respectively, under the pump tax and water duty policies in the year 2000.

Surface water use changes very slightly under each investment scenario. In the constrained investment scenario surface water use increases only 0.9 percent with the pump tax and 1.5 percent with the water duty in the year 1990.

In the year 2000, surface water use increases 0.7 percent and 0.4 percent, respectively, under the pump tax and water duty

TABLE 11

NET REVENUES IN THE PAMA "WITH INVESTMENT" CONSTRAINT AND "WITHOUT INVESTMENT" CONSTRAINT

	No AGWMA Policies $	Pump Tax Policy $	Water Duty Policy $
<u>With Investment Constraint</u>			
Base	68,173,641		
1990	73,354,882	71,340,886	65,947,849
Percent over/under base with no AGWMA policies		(2.7)	(10.1)
2000	77,512,824	72,640,487	58,558,920
Percent over/under base with no AGWMA policies [1]		(6.3)	(24.5)
<u>Without Investment Constraint</u>			
Base	68,706,878		
1990	75,150,885	72,320,293	66,621,430
Percent over/under base with no AGWMA policies		(3.8)	(11.3)
2000	77,977,446	73,426,516	59,228,089
Percent over/under base with no AGWMA policies [1]		(5.8)	(24.0)

[1]Brackets denote percentage decreases.

Source: RLPM solution results.

TABLE 12

WATER SUPPLIES USED IN THE PAMA "WITH INVESTMENT" CONSTRAINT AND "WITHOUT INVESTMENT" CONSTRAINT

	Groundwater			Surface Water		
	No AGWMA Policies	Pump Tax Policy	Water Duty Policy	No AGWMA Policies	Pump Tax Policy	Water Duty Policy
	acre-feet	acre-feet	acre-feet	acre-feet	acre-feet	acre-feet
With Investment Constraint						
Base	783,951			616,940		
1990	755,253	738,434	543,783	590,634	596,148	599,486
Percent over/under base with no AGWMA policies		(2.2)	(28.0)		0.9	1.5
2000	656,095	631,052	227,827	564,026	567,703	546,240
Percent over/under base with no AGWMA policies[1]		(3.8)	(65.3)		0.7	.04
Without Investment Constraint						
Base	775,224			606,406		
1990	752,590	743,098	546,694	596,950	596,144	599,136
Percent over/under base with no AGWMA policies		(1.3)	(27.4)		(0.1)	0.4
2000	651,524	637,079	233,711	570,517	578,370	564,507
Percent over/under base with no AGWMA policies[1]		(2.2)	(64.1)		1.4	(1.1)

[1]Brackets denote percentage decreases.

Source: RLPM solution results.

policies.

In the unconstrained investment case, surface water use decreases slightly by 0.1 percent under the proposed pump tax and increases 0.4 percent under the proposed water duty in the year 1990. For the year 2000, surface water use increases 1.4 percent under the pump tax but decreases 1.1 percent under the water duty policy.

Electrical energy used, on a regional level, for both groundwater pumping and pressurization of irrigation systems is also affected by the proposed policies of the 1980 AGWMA. As shown in Table 13, when investment is constrained, energy use decreases 2.3 percent and 28.1 percent under the proposed pump tax policy and proposed water duty policy, respectively, in the year 1990. In the year 2000, energy use declines 13.0 percent and 72.5 percent, respectively, under the proposed pump tax and water duty when compared to energy use that results when neither policy is enacted.

In the unconstrained investment scenario, electrical energy use decreases 1.0 percent and 40.8 percent, respectively, under the pump tax and the water duty policies, in the year 1990. Energy use declines, in the year 2000, by 10.6 percent and 69.2 percent, respectively, with the proposed pump tax and water duty policies.

Table 14 shows the existing number of acres of the five irrigation systems assumed to exist within the PAMA and the additional investment in these irrigation technologies which occurs

TABLE 13

ELECTRICAL ENERGY USED IN THE PAMA "WITH INVESTMENT" CONSTRAINT AND "WITHOUT INVESTMENT" CONSTRAINT

	No AGWMA Policies Million KWH	Pump Tax Policy Million KWH	Water Duty Policy Million KWH
With Investment Constraint			
Base	621.9		
1990	608.3	594.5	437.5
Percent over/under base with no AGWMA policies		(2.3)	(28.1)
2000	610.3	531.0	167.7
Percent over/under base with no AGWMA policies[1]		(13.0)	(72.5)
Without Investment Constraint			
Base	640.7		
1990	607.1	601.3	436.1
Percent over/under base with no AGWMA policies		(1.0)	(40.8)
2000	608.5	543.8	187.5
Percent over/under base with no AGWMA policies[1]		(10.6)	(69.2)

[1]Brackets denote percentage decreases.

Source: RLPM solution results.

TABLE 14

INVESTMENT IN ALTERNATIVE IRRIGATION TECHNOLOGIES IN THE PAMA "WITH INVESTMENT" CONSTRAINT AND "WITHOUT INVESTMENT" CONSTRAINT

Technology	Base No AGWMA Policies: Existing Acres	Base No AGWMA Policies: Additional Acres	1990 No AGWMA Policies	1990 Additional Acres: Pump Tax Policy	1990 Additional Acres: Water Duty Policy	2000 No AGWMA Policies	2000 Additional Acres: Pump Tax Policy	2000 Additional Acres: Water Duty Policy
With Investment Constraint								
Conventional Surface Flood	273,823							
Laser Level Surface Flood	12,200			5,250	19,054		7,524	585
Center Pivot Sprinkler	915							
Linear Move Sprinkler	488	65,530		3,465	9,914		1,408	531
Drip	27							
Capital Cost of Investment (Millions of Dollars)		37.3		8.0	15.2		5.8	.7
Without Investment Constraint								
Conventional Surface Flood	273,823							
Laser Level Surface Flood	12,200	5,293	5,814	5,814	22,078	6,674	6,674	
Center Pivot Sprinkler	915							
Linear Move Sprinkler	488	106,446	1,222	1,142	1,005	2,937	3,896	531
Drip	27							
Capital Cost of Investment (Millions of Dollars)		55.1	4.6	4.5	15.6	6.0	6.5	.3

Source: RLPM solution results

under each investment scenario. In addition, the amount of capital required for the additional investment is also shown in Table 14 for each investment scenario.

In the constrained investment case, over 65,500 acres of linear move sprinkler technology are added through investment in the base solution at a cost of over $37 million. The 65,500 acres of the linear move sprinkler system are taken out of the existing 273,800 acres of conventional surface flood irrigation acres with the PAMA. In other words, the total number of conventional surface flood irrigation acres is reduced by the number of acres of alternative irrigation technologies which are added through investment in each investment scenario.

In the year 1990, 5,250 additional acres of laser level surface and 3,465 acres of linear move sprinkler technologies are added at an investment cost of $8 million under the proposed pump tax. Investment of over $15 million results under the proposed water duty policy in the year 1990. In this case, 19,054 acres of laser level surface and 9,914 acres of linear move sprinkler technologies are added to the region (PAMA) in the constrained investment case.

In the year 2000, an investment of $5.8 million results. Over 7,500 acres of laser level surface and just over 1,400 acres of linear move sprinkler technologies are added under the proposed pump tax. Under the proposed water duty policy, a total of 585 acres of laser level surface and 531 acres of linear move sprinkler technologies are added at a cost of $700,000 to the region in the year 2000.

In the unconstrained investment scenario, additional acres of both laser level surface and linear move sprinkler technologies occurs in the base solution at an investment cost of just over $55 million. A total of 5,293 acres of laser level surface and 106,446 acres of linear move sprinkler technology are taken out of the 273,800 acres of conventional surface flood in the base solution.

In the year 1990, investment of $4.6 million occurs when neither proposed policy of the 1980 AGWMA is enacted, as shown in Table 14. Over 5,800 acres and 1,220 acres of laser level surface and linear move sprinkler are added, respectively, to the mix of irrigation technologies within the region. Under the proposed pump tax, over 5,800 acres of laser level surface and over 1,140 acres of linear mover sprinkler technologies are added at an investment cost of $4.5 million. Investment also occurs under the proposed water duty in the year 1990. In this case, over 22,000 acres of laser level surface and just over 1,000 acres of linear move sprinkler technologies are added at an investment cost of $15.6 million.

In the year 2000, investment of $6.0 million occurs when neither policy is enacted. In this case, 6,674 acres of laser level surface and 2,937 acres of linear move sprinkler technologies are added. Under the proposed pump tax, in the year 2000, over 6,670 acres of laser level surface and over 3,890 acres of linear move sprinkler technologies are added at an investment cost of $6.5

million. Investment in 531 acres of linear move sprinkler occurs, in the year 2000, under the proposed water duty policy in the unconstrained investment case. The cost of this investment is $300,000.

The adoption of the proposed policies of the 1980 AGWMA will also affect the amount and type of cropped acreage grown in the PAMA. Table 15 summarizes the cropped acreage grown in the PAMA under each investment constraint. Since the reduction in cropped acres due to urban expansion has been accounted for within each model, the acreage totals found in Table 15 reflect the impact of the proposed AGWMA policies solely.

In the case of constrained investment, cropped acreage decreases 0.5 percent and 13.8 percent under the proposed pump tax and water duty policies, respectively, in the year 1990. In the year 2000, cropped acreage declines 0.5 percent under the pump tax and 33.9 percent under the water duty, respectively.

When investment is unconstrained, cropped acreage shows virtually no change under the proposed pump tax policy and a decrease of 12.9 percent under the proposed water duty policy in the year 1990. Cropped acreage shows a slight decrease of 0.3 percent under the pump tax policy and a decrease of 33.5 percent under the water duty policy in the year 2000.

TABLE 15

CROPPED ACREAGE IN THE PAMA "WITH INVESTMENT" CONSTRAINT AND "WITHOUT INVESTMENT" CONSTRAINT

Crop	No AGWMA Policies			Pump Tax Policy		Water Duty Policy	
	Base	1990	2000	1990	2000	1990	2000
With Investment Constraint							
Alfalfa	55,815	53,525	51,409	52,775	47,498	52,460	39,344
Upland Cotton	112,349	114,022	100,121	117,150	107,068	90,944	54,801
Pima Cotton	14,972	16,350	17,427	13,192	13,356	12,604	11,044
Barley	4,501	2,775	820	1,702	768	1,388	106
Wheat	25,280	25,055	20,430	26,154	20,885	22,278	17,579
Sorghum	8,017	6,150	7,138	5,238	6,376	5,238	1,934
Sugar Beets	4,275	2,418	2,879	1,695	1,962	2,296	1,664
Spring Lettuce	3,487	6,126	11,039	6,632	11,916	6,632	11,824
Fall Lettuce	3,325	4,788	6,979	5,481	8,094	4,948	7,234
Safflower	2,363	3,633	5,588	3,759	5,800	3,759	2,527
Total Acreage	234,384	234,842	223,830	233,778	223,723	202,547	148,057
Percent over/under base with no AGWMA policies[1]				(0.5)	(.05)	(13.8)	(33.9)

[1]Brackets denote percentage decreases.

(continued)

TABLE 15 (continued)

Crop	No AGWMA Policies			Pump Tax Policy		Water Duty Policy	
	Base	1990	2000	1990	2000	1990	2000
Without Investment Constraint							
Alfalfa	53,226	55,090	52,141	54,141	48,645	53,290	39,326
Upland Cotton	122,168	113,206	100,951	116,207	106,950	91,046	54,655
Pima Cotton	15,499	16,350	17,427	13,229	13,435	12,637	11,104
Barley	4,501	1,785	820	1,702	768	1,388	106
Wheat	26,659	24,982	20,400	26,107	21,098	22,298	17,652
Sorghum	8,017	6,150	7,138	5,238	6,375	5,238	1,934
Sugar Beets	3,790	3,611	4,465	3,212	3,215	3,489	3,491
Spring Lettuce	3,487	6,126	11,039	6,632	11,916	6,632	11,917
Fall Lettuce	3,325	4,788	6,975	5,481	8,095	5,481	8,095
Safflower	2,363	3,633	5,588	3,759	5,801	3,759	2,686
Total Acreage	243,035	235,721	226,944	235,708	226,294	205,258	150,966
Percent over/under base with no AGWMA policies[1]				(.006)	(0.3)	(12.9)	(33.5)

[1]Brackets denote percentage decreases.

Source: RLPM solution results

Summary of the Effects of the Proposed Pump Tax and Water Duty Policies in the PAMA

The results given in Tables 11 to 15 bear out the following; regardless of the investment scenario considered, the pump tax is less effective in curtailing groundwater use than is the water duty policy.

The results in Tables 11 and 12 show that, in the constrained investment case, a 2.2 percent decrease in groundwater use due to the proposed pump tax policy results in a 2.7 percent decrease in net revenues in the year 1990. The total decrease in net revenues is $2,013,996. The total number of cropped acres in the PAMA under the pump tax is 233,778, as shown in Table 15. There is a decrease of $8.61 in net revenues per cropped acre under the proposed pump tax in the year 1990.

Similarly, groundwater use decreases 28.0 due to the proposed water duty in the year 1990, in the constrained investment. Net revenues decline 10.1 percent or by $7,407,033. Total cropped acreage in the year 1990 amounts to 202,547 acres. Net revenues decline $36.57 per acre under the proposed water duty.

In the year 2000 groundwater use decreases 3.8 percent and 65.3 percent under the proposed pump tax and water duty policies, respectively. These declines in groundwater use result in decreases in net revenues of 6.3 percent and 24.5 percent, respectively. In absolute terms net revenues decline $4,872,337 and

$18,953,904, respectively from the net revenue which results with no AGWMA policies in effect. Therefore net revenues decline by $21.78 per acre under the pump tax and $128.02 per acre under the water duty when divided by the number of cropped acres which result in the year 2000 under each policy of the AGWMA. The cropped acreage is shown in Table 15.

Since investment in alternative technologies has been stressed as being an important feature of the economic analysis presented in Chapter 2 and the RLPM described in Chapter 4, what mix of technologies is chosen in the empirical results of the RLPM solutions? Table 14 shows that for the region (PAMA) the investment will center on laser level surface and linear move sprinkler technology, in addition to the existing or "inherited" acres of center pivot sprinkler and drip, and regular surface flood systems.

Possible reasons for this mix of irrigation investment include that linear move sprinkler technology has the lowest per acre investment cost of the alternative technologies considered in this study. Even though, center pivot sprinkler technology is assumed to have the same water application efficiency as linear move sprinkler, in this study, linear move is chosen since it is the least expensive technology. Laser level surface is assumed to have the highest water application efficiency of the alternative technologies included in this study. In addition it is less expensive per acre than drip. Laser level is chosen over center pivot sprinkler systems even though, on a per acre basis, center pivot technology is less expensive than laser level technology. Since laser level technology was chosen despite the per acre cost advantage enjoyed by center pivot systems would seem to imply that the high water application efficiency associated with laser level was a criteria used by the models, in this study, to choose laser level over center pivot sprinkler technology.

A further implication of the mix of irrigation technologies chosen, in this study, is that the high per acre investment cost for drip prohibits its use as a technology. Even in the unconstrained investment scenario (when there was assumed to be unlimited capital investment funds), drip technology was not chosen by the models in this study. Therefore, the investment activity in the models of this study centered on laser level surface and linear move sprinkler technologies.

In terms of crop mixes on a regional (PAMA) level, the general trend in both investment scenarios is for the percentage of cropped acres devoted to grain crops--barley, wheat, and sorghum--to decrease over time. On the other hand, the percentage of cropped acreage of more high-valued spring and fall lettuce increases over the time periods included in this study.

As can be seen in Table 15, a total of 33,980 acres of grain crops were grown in the year 1990 with no AGWMA policies in the constrained investment scenario. In 1990 under the proposed pump tax the percentage of cropped acres in grain crops decreases 2.6

percent while lettuce acreage increases by 11.0 percent. In the year 2000, grain crops decrease by 1.3 percent while lettuce crops increase by 11.1 under the pump tax when compared to the no AGWMA policy solution.

Comparing the cropped acreage totals of grain crops and lettuce with no AGWMA policies to the cropped acres resulting under the water duty in the year 1990, reveals that the percentage of cropped acres in grain decreases 14.9 percent while the percentage of acreage devoted to lettuce increases by 6.1 percent. In the year 2000, grain acres decrease by 30.9 percent while the percentage of acres devoted to lettuce increases by 5.8 percent.

In the unconstrained investment scenario a total of 32,917 acres of grain crops and 10,914 acres of lettuce were grown in the year 1990 with no AGWMA policies. In 1990, under the proposed pump tax, the number of acres of grain crops increase slightly by 0.4 percent while lettuce acreage increases by 11.0 percent. In the year 2000, the total number of acres of grain crops decrease by 0.4 percent while lettuce acreage increases by 11.1 percent when compared to the total acreage of grain crops and lettuce in 2000 when no policies are enacted.

In the year 1990, under the water duty policy, total acreage of grain crops decreases 12.1 percent while acreage of lettuce increases 1.0 percent when compared to the result with no AGWMA policies. In 2000, the total acreage of grain crops declines 30.6 percent while lettuce acreage increases 11.1 percent in comparison to the total acreage of grain crops and lettuce when no policies of the 1980 AGWMA are enacted.

A total summary of the effects of the proposed pump tax policy and water duty policy are presented in Tables 16 and 17.

TABLE 16

SUMMARY OF EFFECTS OF PROPOSED PUMP TAX AND WATER DUTY ON AGRICULTURE IN THE PAMA, "WITH INVESTMENT" CONSTRAINT

	Summary						
	No AGWMA Policies			Pump Tax		Water Duty	
	Base	1990	2000	1990	2000	1990	2000
Net Revenue	68,173,641	73,354,882	77,512,824	71,340,886	72,640,487	65,947,849	58,558,920
Water (Acre-Feet)							
Groundwater	783,951	755,253	656,095	738,434	631,052	543,783	227,827
Surface Water	616,940	590,634	564,026	596,148	567,703	599,486	564,240
Energy (Million KWH)	621.9	608.3	610.3	594.5	531.0	437.5	167.7
Total Acreage	234,384	234,842	223,830	233,778	223,723	202,547	148,057
Irrigation Technologies (Acres)							
Laser Level	12,200			5,250	7,524	19,054	585
Center Pivot	915						
Linear Move	64,018			3,465	1,408	9,914	531
Drip							
Investment in Alternative Technologies (Millions of Dollars)	37.3			8.0	5.8	15.7	.7

Source: RLPM solution results

TABLE 17

SUMMARY OF EFFECT OF PROPOSED PUMP TAX AND WATER DUTY ON AGRICULTURE IN THE PAMA, "WITHOUT INVESTMENT" CONSTRAINT

	Summary						
	No AGWMA Policies			Pump Tax		Water Duty	
	Base	1990	2000	1990	2000	1990	2000
Net Revenue	68,706,878	75,150,885	77,977,446	72,320,293	73,426,516	66,621,430	59,228,089
Water (Acre-Feet)							
Groundwater	775,224	752,590	651,524	743,098	637,079	546,694	233,711
Surface Water	606,406	596,950	570,517	596,144	578,370	599,136	564,507
Energy (Million KWH)	640.7	607.1	608.5	601.3	543.8	436.1	187.5
Total Acreage	243,035	235,721	226,944	235,708	226,294	205,258	150,966
Irrigation Technologies (Acres)							
Laser Level	17,493	5,814	6,674	5,814	6,674	22,078	
Center Pivot	915						
Linear Move	106,934	1,222	2,937	1,142	3,896	1,005	531
Drip	27						
Investment in Alternative Technologies (Millions of Dollars)	55.1	4.6	6.9	4.5	6.5	15.6	.3

Source: RLPM solution results

CHAPTER 6

CONCLUSIONS

Based on the empirical results of the RLPM used in this study the effects of the proposed policies of the 1980 AGWMA will bring about changes in agriculture in the PAMA. The model results of this study, as shown in Tables 16 and 17 above, would indicate the following changes in the PAMA due to implementation of the proposed policies of the 1980 AGWMA:

1. Net revenues will decline over the time periods of this study. Declines of up to 5.8 percent and 24.5 percent may be expected with the pump tax and water duty, respectively.
2. Groundwater use will decline but much less with the pump tax policy. Groundwater use with the proposed pump tax may be expected to decrease by only 3.8 percent, while the water duty may lead to groundwater use reductions of up to 65.3 percent.
3. Electrical energy use also declines over the time periods of this study. Energy use may decline by as much as 13.0 percent under the pump tax, and by 72.5 percent with the proposed water duty.
4. Investment in alternative irrigation technologies may be expected to occur. In this study, laser level surface and linear move sprinkler were chosen by the RLPM models. From a total of 287,453 estimated existing acres in the PAMA in the base

solution, the proportion of the total acres composed of laser level and linear move technologies could be 6.0 percent and 39.0 percent, respectively, under the pump tax and up to 10.0 percent and 38.0 percent, respectively, under the water duty. The relative amounts of laser level and linear move technology in the PAMA by the year 2000 are shown in Table 18.

5. Crop mix changes may be expected due to the imposition of the proposed pump tax and water duty policies. In this study, the general trend reflected a percentage decline over time in the grain crops--barley, wheat, and sorghum--and a percentage increase in more high-valued "specialty" crops--spring and fall lettuce.

If investment is to play a pivotal role in the PAMA as a result of the enactment of the proposed policies of the 1980 AGWMA, sufficient capital must be available for investment in alternative irrigation technologies. In this study, an estimated $37.3 million dollars would be needed to achieve the level of investment in the base solution in the constrained investment scenario. In contrast, when investment is unconstrained, $55.1 million dollars would be needed to achieve the level of investment in laser level and linear move technology indicated for the base solution. The difference in investment funds needed for the base solutions amounts to 47.7 percent when considering the unconstrained scenario relative to the constrained scenario. These figures make it clear that in order for

TABLE 18

RELATIVE AMOUNTS OF LASER LEVEL SURFACE AND LINEAR MOVE SPRINKLER TECHNOLOGIES IN THE PAMA BY THE YEAR 2000 AS A RESULT OF INVESTMENT "WITH INVESTMENT" CONSTRAINT AND "WITHOUT INVESTMENT" CONSTRAINT

	Base Additional Acres	1990		2000	
		Pump Tax	Water Duty	Pump Tax	Water Duty
		With Investment Constraint[a]			
Laser Level		5,250	19,054	7,524	585
Percent of Laser Level Surface Relative to Total Acres by 2000				4.0	7.0
Linear Move	63,530	3,465	9,914	1,408	531
Percent of Linear Move Sprinkler Relative to Total Acres by 2000				24.0	26.0
		Without Investment Constraint			
Laser Level	5,293	5,814	22,078	6,674	
Percent of Laser Level Surface Relative to Total Acres by 2000				6.0	10.0
Linear Move	106,446	1,142	1,005	3,896	531
Percent of Linear Move Sprinkler Relative to Total Acres by 2000				39.0	38.0

[a]Total Existing Acres of All Technologies = 287,453

Source: RLPM Solution Results

investment to occur substantial amounts of capital would need to be made available to the districts in the PAMA. At present, programs do exist that are designed to help farmers defray some of the expense of irrigation technology investment. Daubert and Ayer (1982) report that a cost-sharing program offered by the Agricultural Stabilization and Conservation Service (ASCS) covers up to as much as 50 percent of investment costs in laser level surface technology up to a maximum of $3,500 per year. In comparison, the results of this study would indicate that the available funds for investment will need to be quite substantial for significant amounts of investment in water application efficient irrigation technologies to occur.

Finally, the mix of irrigation technologies, indicated in this study, is similar to the trend noted elsewhere; namely, that ". . . recent trends in the most efficient irrigation systems are toward sprinkler irrigation, [and] dead level irrigation . . ." (Erie, 1968), p. 292). The results of this study also indicate that investment in drip irrigation will not occur in the PAMA due to the high per acre cost, even though the number of acres of drip is currently increasing outside the boundaries of the PAMA.

Other Implications for Policy

Besides researchers interested in Arizona groundwater use problems and who may be attempting to assess the potential effects of policies such as the 1980 AGWMA on groundwater use, the results of this study could be utilized by policymakers who are given the task of formulating such policies.

Suppose that policymakers within the Arizona Department of Water Resources (ADWR) want to achieve similar percentage decreases in groundwater use by the year 2000 under the pump tax as under the water duty policy. The proposed five dollar per acre-foot pump tax will not result in the desired percentage decreases in groundwater use as shown in Table 12 above. However, the choice of a unit tax or subsidy has much to recommend its use as an instrument to help achieve the desired decrease in groundwater use. "Unit taxes [or subsidies] appear to represent a very attractive method for the realization of specified standards . . . Not only do they require relatively little in the way of detailed information on the cost structure of different industries [or firms], but they lead automatically to the least-cost pattern of modification of . . . activities." (Baumol and Oates, 1975, p. 140). In other words, the use of a tax on groundwater use would allow a particular farmer within an irrigation district to choose unit-by-unit the least-cost combination of crop production activities that would minimize costs and thus maximize profits. The use of a pump tax can result in the application of the equi-marginal principle which means that from an economic standpoint the resulting level of groundwater use is the most efficient and that no other combination of groundwater use by an individual farmer would result in lower costs and higher profits.

Tables 19 and 20 indicate the estimated amount by which the pump tax may be increased in the year 2000 from the year 1990 and thereby reduce groundwater use under the pump tax policy to attain similar reductions in groundwater use as result under the water duty policy. In the year 1990, the cost per acre-foot of groundwater under the pump tax will increase by $3 over the base period in each district. In the year 2000, under the water duty, the cost per acre-foot of groundwater will also be $3 higher than the base period since the 1980 AGWMA specifies that the pump tax will have been levied by the year 2000 in conjunction with the water duty (Summary, Groundwater Management Act, 1980).

The first three columns of Tables 19 and 20 show the cost per acre-foot of groundwater in the base period and the increases in groundwater costs in 1990 and 2000 under the proposed pump tax of the 1980 AGWMA. Column 4 shows the estimated average cost per acre foot for groundwater pumping activities with the water duty policy in the year 2000. Column 5 of Tables 19 and 20 shows the difference between the proposed pump tax in the year 2000 (which equals $5 per acre-foot in total) and the upper limit that could be charged for the proposed pump tax to achieve groundwater use reductions similar to those under the water duty policy in the year 2000.

TABLE 19

ESTIMATED INCREASES IN THE PUMP TAX FROM 1990 TO 2000 NEEDED TO ACHIEVE REDUCTIONS IN GROUNDWATER USE IN THE YEAR 2000 AS UNDER THE WATER DUTY POLICY "WITH INVESTMENT" CONSTRAINT

	Cost of Groundwater Per Acre-Foot				
District	(1) Base Period	(2) With Pump Tax[a] 1990	(3) With Pump Tax[a] 2000	(4) Upper Limit Water Duty[b] 2000	(5) Increase in Pump Tax (4) - (3)
SRP	25.00	28.00	30.00	43.32	13.32
BID	7.75	10.75	12.75	11.66	(1.09)
MCMWCD	15.00[c] 33.35[d]	18.00 36.35	20.00 38.35	62.52 76.24	41.52 37.89
RID	17.50	20.50	22.50	165.90	143.40
RWCD	26.00	29.00	31.00	130.46	99.46
QCID	64.41	67.41	69.41	193.37	123.96
TID	33.35	36.35	38.35	163.69	125.34
MID	53.38	56.38	58.38	219.96	161.58

[a]Reflects $3 and $2 per acre-foot tax, respectively, as proposed in 1980 AGWMA.

[b]Average cost per acre-foot of groundwater for pumping activities with the water duty policy in the year 2000.

[c]District costs for groundwater.

[d]Private farm costs for pumping groundwater.

Source: RLPM Solution Results.

TABLE 20

ESTIMATED INCREASES IN THE PUMP TAX FROM 1990 TO 2000 NEEDED TO ACHIEVE REDUCTIONS IN GROUNDWATER USE IN THE YEAR 2000 AS UNDER THE WATER DUTY POLICY "WITHOUT INVESTMENT" CONSTRAINT

	Cost of Groundwater Per Acre-Foot				
District	(1) Base Period	(2) With Pump Tax 1990	(3) With Pump Tax 2000	(4) Upper Limit Water Duty 2000	(5) Increase in Pump Tax (4) - (3)
SRP	25.00	28.00[a]	30.00[a]	44.40[b]	14.40
BID	7.75	10.75	12.75	11.66	(1.09)
MCMWCD	15.00[c]	18.00	20.00	61.80	41.80
	33.35[d]	36.35	38.35	73.56	35.21
RID	17.50	20.50	22.50	206.44	183.94
RWCD	26.00	29.00	31.00	166.61	135.61
QCID	64.41	67.41	69.41	193.37	123.96
TID	33.35	36.35	38.35	136.41	98.06
MID	53.38	56.38	58.38	218.57	160.19

[a]Reflects $3 and $2 per acre-foot tax, respectively, as proposed in 1980 AGWMA.

[b]Average cost per acre-foot of groundwater for pumping activities with the water duty policy in the year 2000.

[c]District costs for groundwater.

[d]Private farm costs for pumping groundwater.

Source: RLPM Solution Results.

Column 5 reveals that, in general, the estimated increase in cost of groundwater in the irrigation districts with access to both surface water and groundwater is much lower than for districts which depend solely upon groundwater supplies. In one district, the Buckeye Irrigation District, the results of Tables 19 and 20 reveal that the pump tax should actually be reduced by $1.09 (indicated by brackets) per acre foot by the year 2000. The reason that the pump tax should be reduced in the year 2000 can be seen in Table 21. In the year 2000, less water is used with the pump tax than under the water duty so that the pump tax is more constraining from the water duty in the BID. In the other districts, the water duty is the more restraining of the two proposed policies on groundwater use in the year 2000 and therefore the pump tax would need to be raised by the estimated amounts in Tables 19 and 20 to achieve groundwater use reductions similar to those under the water duty policy.

Based on the results in Tables 19 and 20, it is evident that substantial increases in the pump tax would have to be implemented if policymakers would indeed decide to use a pump tax to achieve similar decreases in groundwater use as under the water duty by the year 2000. The impacts upon net revenues, energy use, crop mixes, and investment in irrigation technologies would change under such a pump tax policy and would need to be reassessed to reflect the increases in the pump tax.

TABLE 21

GROUNDWATER SUPPLIES USED IN EACH IRRIGATION DISTRICT
"WITH INVESTMENT" CONSTRAINT AND "WITHOUT INVESTMENT" CONSTRAINT

	SRP	BID	MCMWCD	RID	RWCD	QCID	TID	MID
			With Investment Constraint					
Groundwater (Acre Feet)								
Pump Tax								
1990	203,171	13,846	46,362	186,880	59,826	71,146	58,674	98,529
2000	97,726	12,805	42,445	192,748	52,828	75,056	58,674	98,770
Water Duty								
1990	198,640	14,685	24,087	113,687	52,967	39,676	52,266	47,775
2000	93,151	13,885	14,523	43,535	20,901	11,798	16,740	13,294
Surface Water (Acre Feet)								
Pump Tax								
1990	337,147	110,046	30,109		118,846			
2000	307,125	112,234	29,675		118,669			
Water Duty								
1990	340,341	111,222	29,651		118,272			
2000	321,908	109,894	17,582		114,856			

(continued)

TABLE 21 (continued)

	SRP	BID	MCMWCD	RID	RWCD	QCID	TID	MID
			Without Investment Constraint					
Groundwater (Acre Feet)								
Pump Tax								
1990	203,170	13,846	46,362	186,812	59,828	71,146	58,674	103,260
2000	97,726	12,805	42,444	186,937	59,947	75,028	58,674	103,518
Water Duty								
1990	198,640	14,685	23,455	113,680	53,153	39,677	52,266	51,138
2000	93,151	13,885	14,928	44,690	21,082	11,798	16,740	17,435
Surface Water (Acre Feet)								
Pump Tax								
1990	337,147	110,043	30,109		188,845			
2000	307,125	112,234	25,079		119,149			
Water Duty								
1990	340,341	111,222	29,651		117,923			
2000	321,908	109,894	17,134		115,574			

Source: RLPM Solution Results

Recommendations for Further Research

The results of this study can be broadened and improved upon if data could be incorporated in the models which would reflect: (1) possible decreases in the per acre investment costs for alternative irrigation technologies, one example being drip; (2) crop yield variations according to individual irrigation technologies; and (3) changing input and output prices. An additional improvement would make incorporation of crop yield differences for drip irrigation in comparison to other irrigation technologies.

While these recommendations should improve the results of the models, the improvement should be one of degree and not of kind. The results, presented in this study, can provide a foundation for identifying important changes that agriculture, within the PAMA, may undergo as a result of the implementation of the proposed pump tax and water duty policies of the 1980 AGWMA.

APPENDIX A

PERCENT OF TOTAL VARIABLE COST OF PRODUCING A CROP UNDER SURFACE FLOOD IRRIGATION TECHNOLOGY, COMPRISED OF TOTAL VARIABLE COST OF WATER, BY AREA, BY CROP, AND BY COST OF WATER

APPENDIX A: PERCENT OF TOTAL VARIABLE COST OF PRODUCING A CROP, UNDER SURFACE FLOOD IRRIGATION TECHNOLOGY, COMPRISED OF TOTAL VARIABLE COST OF WATER BY AREA, BY CROP AND BY COST OF WATER

Area	Crop	Cost of Producing An Acre of Crop Minus Variable Cost of Water ($/Acre)	Total Variable Cost of Water ($/Acre)		Total Variable Cost of Crop Production ($/Acre)		TVC of Water as Percent of TVC Per Acre (%)	
		Regular Surface Irrigation	With Pump Water	With Surface Water	Pump Water	Surface Water	Pump Water	Surface Water
SRP								
	Alfalfa	201.07	251.26	72.99	452.33	274.06	56	27
	Upland Cotton	492.60	142.90	41.51	635.50	534.11	22	8
	Pima Cotton	489.37	142.90	41.51	632.27	530.88	23	8
	Barley	139.46	115.44	33.53	254.90	172.99	45	19
	Wheat	153.66	89.44	25.98	243.10	179.64	37	14
	Sorghum	119.59	87.98	25.56	207.57	145.15	42	18
	Sugar Beets	437.08	148.51	43.14	585.59	480.22	25	9
	Safflower	115.96	157.46	45.74	273.42	161.70	58	28
	Spring Lettuce	1,723.98	29.33	8.52	1,753.31	1,732.50	2	.5
	Fall Lettuce	1,723.98	29.33	8.52	1,753.31	1,732.50	2	.5
BID								
	Alfalfa	201.07		78.04		279.11		28
	Upland Cotton	492.60		44.38		536.98		8
	Barley	139.46		35.85		175.31		20
	Wheat	153.66		27.78		181.44		15
	Sorghum	119.59		27.33		146.92		19
MCMWCD								
	Upland Cotton	492.60	190.99	85.88	683.59	578.48	28	15
	Barley	139.46	154.29	69.38	293.75	208.84	53	33
	Spring Lettuce	1,723.98	39.20	17.63	1,763.18	1,741.61	2	1
	Fall Lettuce	1,723.98	39.20	17.63	1,763.18	1,741.61	2	1

(continued)

Area	Crop	Cost of Producing An Acre of Crop Minus Variable Cost of Water ($/Acre)	Total Variable Cost of Water ($/Acre)		Total Variable Cost of Crop Production ($/Acre)		TVC of Water as Percent of TVC Per Acre (%)	
		Regular Surface Irrigation	With Pump Water	With Surface Water	Pump Water	Surface Water	Pump Water	Surface Water
RID								
	Alfalfa	201.07	176.37		377.44		47	
	Upland Cotton	492.60	100.30		592.90		17	
	Pima Cotton	489.37	100.30		589.67		17	
	Barley	139.46	81.03		220.49		37	
	Wheat	153.66	62.78		216.44		29	
	Sugar Beets	437.08	104.24		541.32		19	
	Safflower	115.96	110.52		226.48		49	
RWCD								
	Alfalfa	201.07		261.77		462.84		57
	Upland Cotton	492.60		149.08		641.68		23
	Pima Cotton	489.37		149.08		638.45		23
	Barley	139.46		120.27		259.73		46
	Wheat	153.66		93.18		246.84		38
	Sorghum	119.59		91.66		211.25		43
	Sugar Beets	437.08		154.72		591.80		26
	Spring Lettuce	1,723.98		30.55		1,754.53		2
	Fall Lettuce	1,723.98		30.55		1,754,53		2
QCID								
	Upland Cotton	533.98	368.92		902.90		41	
	Pima Cotton	530.75	368.92		899.67		41	
	Wheat	175.47	230.91		406.38		57	
	Sorghum	136.53	227.15		363.68		62	
TID								
	Alfalfa	232.65	335.82		568.47		59	
	Upland Cotton	533.98	190.99		724.97		26	
	Wheat	175.47	119.54		295.01		41	
	Barley	158.08	154.29		312.37		49	

(continued)

Area	Crop	Cost of Producing An Acre of Crop Minus Variable Cost of Water ($/Acre)	Total Variable Cost of Water ($/Acre)		Total Variable Cost of Crop Production ($/Acre)		TVC of Water as Percent of TVC Per Acre (%)	
		Regular Surface Irrigation	With Pump Water	With Surface Water	Pump Water	Surface Water	Pump Water	Surface Water
MID								
	Upland Cotton	533.98	305.72		839.70		36	
	Wheat	175.47	191.35		366.82		52	
	Barley	158.08	246.98		405.06		61	
	Sugar Beets	477.80	317.73		795.53		40	
	Spring Lettuce	1,723.98	62.75		1,786.73		4	
	Fall Lettuce	1,723.98	62.75		1,786.73		4	

Source: Representative farm budgets and district water costs from irrigation district offices and Hathorn and Farr 1982 Arizona Field Crop Budgets, Maricopa County.

APPENDIX B:

AMOUNT OF WATER APPLIED PER ACRE, BY IRRIGATION TECHNOLOGY, AND BY CROP IN THE STUDY AREA IN ORDER TO SATISFY THE CONSUMPTIVE USE OF EACH CROP

APPENDIX B: AMOUNT OF WATER[1] APPLIED PER ACRE, BY IRRIGATION TECHNOLOGY, AND BY CROP IN THE STUDY AREA IN ORDER TO SATISFY THE CONSUMPTIVE USE OF EACH CROP

	Alfalfa					Upland Cotton				
CROP TECHNOLOGY	Regular Surface	Laser Level Surface	Center Pivot	Linear Move	Drip	Regular Surface	Laser Level Surface	Center Pivot	Linear Move	Drip
Water Applied Per Acre	120.8	82.5	92.9	92.9		68.7	45.8	51.5	51.5	48.5
	Pima Cotton					Barley				
CROP TECHNOLOGY	Regular Surface	Laser Level Surface	Center Pivot	Linear Move	Drip	Regular Surface	Laser Level Surface	Center Pivot	Linear Move	Drip
Water Applied Per Acre	68.7	45.8	51.5	51.5	48.5	42.1	28.1	31.6	31.6	
	Wheat					Sorghum				
CROP TECHNOLOGY	Regular Surface	Laser Level Surface	Center Pivot	Linear Move	Drip	Regular Surface	Laser Level Surface	Center Pivot	Linear Move	Drip
Water Applied Per Acre	43.0	28.7	32.3	32.3		42.3	28.2	31.7	31.7	
	Sugar Beets					Spring Lettuce				
CROP TECHNOLOGY	Regular Surface	Laser Level Surface	Center Pivot	Linear Move	Drip	Regular Surface	Laser Level Surface	Center Pivot	Linear Move	Drip
Water Applied Per Acre	71.4	47.6	53.5	53.5		14.1	9.4			10.0
	Fall Lettuce					Safflower				
CROP TECHNOLOGY	Regular Surface	Laser Level Surface	Center Pivot	Linear Move	Drip	Regular Surface	Laser Level Surface	Center Pivot	Linear Move	Drip
Water Applied Per Acre	14.1	9.4			10	75.7	50.5	56.7	56.7	

Source: Cooperative Extension Service, Consumptive Use Charts, 1979. Based on Erie, French, and Harris. Calculations made assuming the following irrigation technology efficiencies: regular surface 60%, laser level surface 90%, center pivot and linear move 80%, and drip 85%.

[1]Measured in acre-inches of water per acre.

APPENDIX C

MATHEMATICAL STATEMENT OF THE RECURSIVE LINEAR PROGRAMMING MODEL, RLPM, USED IN THIS STUDY

Mathematical Model

$$\text{Max NR} = \sum_{i=1}^{11} P_i Q_i - \sum_{j=1}^{10} \sum_{s=1}^{8} \sum_{k=1}^{5} C_{jsk} \cdot X_{jsk} - \sum_{t=1}^{12} C_t^{pw} \cdot PW_t$$

$$- \sum_{t=1}^{12} EP^{pw} \cdot QE_t - \sum_{t=1}^{12} C_t^{sw} \cdot QSW_t - \sum_{t=1}^{12} \sum_{k=1}^{5} EP^{Pres} \cdot QE_{tk}$$

$$- \sum_{k=1}^{4} SCSTEA_k \cdot X_k - \sum_{k=1}^{4} SCSTAA_k \cdot X_k$$

subject to:

(Land Constraint)

$$\sum_{j=1}^{10} \sum_{k=1}^{5} X_{jsk} \leq LAND_s \qquad s=1,\ldots,8$$

(Commodity Balance Row)

$$\sum_{j=1}^{10} \sum_{s=1}^{8} Y_{ijsk} \cdot X_{jsk} - QS_i = 0 \qquad t=1,\ldots,11$$

(Water Balance Row)

$$\sum_{j=1}^{10} \sum_{s=1}^{8} \sum_{k=1}^{5} WR_{jskt} \cdot X_{jskt} - WU_t^{(P+S)} = 0 \qquad i=1,\ldots,12$$

(Pump Water Constraint)

$$\sum_{j=1}^{10} \sum_{s=1}^{8} \sum_{k=1}^{5} WP_{jskt} \leq PWAV_t \qquad t=1,\ldots,12$$

(Surface Water Constraint)

$$\sum_{j=1}^{10} \sum_{s=1}^{8} \sum_{k=1}^{5} QSW_{jskt} \leq SWAV_t \qquad t=1,\ldots,12$$

(Energy Balance Row)

$$\sum_{t=1}^{12} EIRR_t - EU_t \qquad = 0$$

(Pima Cotton Acreage Constraint)

$$QPC_s \qquad \leqslant PMCOT \quad s=1,\ldots,8$$

(Acreage Flexibility Constraint)

$$X_{jsmk} \geqslant (1-\beta)^j X_{kjs(m-1)} \qquad j=1,\ldots,10$$

$$X_{jsmk} \leqslant (1-\beta)^j X_{ksj(m-1)} \qquad s=1,\ldots,8 \quad m=1,\ldots,4$$

(Irrigation System Pressurization Balance Row)

$$\sum_{t=1}^{12} AI_{tjk} \cdot ERP_k^{AI} - EPRU_k^{AI} \qquad = 0 \qquad j=1,\ldots,10 \quad k=1,\ldots,3$$

(Service Capital Balance Row)

$$\sum_{k=1}^{4} SCSTCAP_k \cdot X_k - SRCAPU_k \qquad = 0$$

(Upper Bound on Existing Acres of Particular Technology Constraint)

$$\sum_{k=1}^{4} AETCH_k^d \qquad \leqslant TOTAC_k$$

(Investment Capital Constraint)

$$\sum_{k=1}^{4} CSTINV_k \cdot X_k \qquad \leqslant TOTCAPAVL$$

where,

i = number of commodities.

d = number of irrigation districts in Maricopa County included in this study.

j = number of crops.

k = number of irrigation technologies considered for the study area.

s = number of soil types.

t = number of time periods in a production year.

NR = net returns above variable cost of production ($).

P_i = market price for the i^{th} commodity ($/unit).

Q_i = quantity of the i^{th} commodity sold (unit).

C_{jsk} = cost of producing the j^{th} crop of the s^{th} soil with the k^{th} irrigation technology ($/acre).

X_{jsk} = number of acres used to produce the j^{th} crop on the s^{th} soil with the k^{th} irrigation technology (acre).

C_t^{pw} = cost per acre-inch for pump water in the t^{th} time period ($/acre-inch).

C_t^{sw} = cost per acre-inch for surface water in the t^{th} time period ($/acre-inch).

QSW_t = quantity of surface water used for irrigation in the t^{th} time period (acre-inch).

PW_t = quantity of pump water used for irrigation in the t^{th} time period (acre-inch).

EP^{Pres} = energy price for pressurizing an irrigation system in order to pump an acre-inch of water ($/acre-inch).

EP^{pw} = energy price for pumping an acre-inch of pump water ($/acre-inch).

QE_{tk} = quantity of energy used in the t^{th} time period to pressurize the k^{th} irrigation system (technology) to pump an acre-inch of water (KWH/acre-inch)

$LAND_s$ = total amount of land of the s^{th} soil type available in a production area (acre).

WR_{jskt} = quantity of water pumped in acre-inches used to produce the j^{th} crop on the s^{th} soil using the k^{th} irrigation technology in the t^{th} time period (acre-inch/acre).

$WU_t^{(P+S)}$ = total amount of pump and surface water used in the t^{th} time period in a production acre (acre-inch).

Y_{ijsk} = yield of the i^{th} commodity from the j^{th} crop grown on the s^{th} soil type using the k^{th} irrigation technology (pounds/acre).

QS_i = quantity of the i^{th} commodity sold (pounds)

WP_{jskt} = quantity of water pumped in acre-inches used to produce the j^{th} crop on the s^{th} soil with the k^{th} technology in the t^{th} time period (acre-inch).

$PWAV_t$ = quantity of pump water available in the t^{th} time period (acre-inch).

QSW_{jskt} = quantity of surface water in acre-inches used to produce the j^{th} crop on the s^{th} soil with the k^{th} technology in the t^{th} time period (acre-inch).

$SWAV_t$ = quantity of surface water available in the t^{th} time period (acre-inch).

$EIRR_t$ = energy required to pump an acre-inch of water for irrigation in the t^{th} time period (KWH/acre-inch).

EU_t = energy used for pumping an acre-inch of water for irrigation in the t^{th} time period (KWH/acre-inch).

QPC_s = quantity of Pima cotton grown on the s^{th} soil type (acre).

PMCOT = acreage constraint placed on Pima cotton for a production year (acre).

$(1-\beta)^j$ = one minus the minimum percentage change in acreage of the j^{th} crop between the m^{th} -1 and the m^{th} management period (percent)

$(1+\beta)^j$ = one plus the maximum percentage change in acreage of the j^{th} crop between the m^{th}-1 and the m^{th} management period (percent)

$X_{kjs(m-1)}$ = acres of the j^{th} crop grown on the s^{th} soil in the m^{th}-1 management period with the k^{th} irrigation technology (acre).

X_{jskm} = acres of the j^{th} crop grown on the s^{th} soil in the m^{th} management period under the k^{th} irrigation technology (acre).

AI_{tjk} = the number of acre inches of water pumped in the t^{th} time period for the j^{th} crop with the k^{th} irrigation technology (acre-inch/acre).

ERP_k^{AI} = amount of energy (electricity required for pressurizing the k^{th} irrigation system to pump AI acre-inches of water (KWH/acre-inch/acre).

$EPRU_k^{AI}$ = amount of energy (electricity) used for pressurizing the k^{th} irrigation system to pump AI acre-inches of water (KWH/acre-inch/acre).

$SCSTCAP_k$ = service cost (depreciation, interest, taxes, insurance) to capital needed for the k^{th} irrigation technology ($/acre).

X_k = number of acres using the k^{th} irrigation technology (acre).

$SRCAPU_k$ = service cost to capital used for the k^{th} irrigation ($/acre).

$AETCH_k^d$ = existing acres of the k^{th} irrigation technology in Maricopa County in each irrigation district d (acre).

$TOTAC_k$ = total existing acres of k^{th} irrigation technology in Maricopa County (acre).

$CSTINV_k$ = cost of investment in the k^{th} irrigation technology ($/acre).

TOTCAPAVL = total capital available for investment in irrigation systems ($).

$SCSTEA_k$ = service cost to existing acres of irrigation technology k ($/acre).

$SCSTAA_k$ = service cost to additional acres of irrigation technology k added through investment ($/acre).

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