THE WATER SECTOR FOR THE CARD/RCA 85 MODEL

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I. INTRODUCTION

Availability of water for agricultural use is one of the major factors determining agricultural production in the Western United States and is becoming an important factor in areas of the Southeast. In addition, water use and conservation is an important concern of the 1977 Soil and Water Resources Conservation Act. Thus, it is necessary to build an agricultural water sector for use in the CARD/RCA85 programming models.

The purpose of this paper is to conceptually explain the proposed CARD/RCA85 water sector, the methodology to be used in coefficient development, and the data requirements. In addition, the paper will address where the data needs can be met and the apparent gaps that appear in the data.

Dr. Supalla addressed the Project Advisory Committee (PAC) outlining concerns that a water sector should address (see the PAC minutes dated March 10-11/83). Following this guide and past works, CARD proposes that the following water sector be considered for use in the CARD/RCA85 programming models.

A Conceptual View

A schematic of a producing area's water sector is shown in Figure 1 with the pertinent producing area constraints and activities. It should be noted that for the sake of space land has been collapsed into two quality land groups rather than the eight land groups that will be used in the CARD/RCA85 programming models. In addition, only two irrigated rotations (IRRROT1 and IRRROT2) are presented. Finally, the land converson activities are displayed in the Figure. However, they are not discussed in this paper.

Constraints

Water requirement constraint: The functional form of the water requirement constraint is:

$$\sum_j CWU_j X_{ij} - \sum_k b_{ik} WA_{ik} \leq 0 \quad (1)$$

i = 1 to 105 for the number of producing areas.

j = 1 ... the number of irrigated rotations[1] within a producing area.

k = 1, 2, 3, 4, 5, 6 for the number of different irrigation systems in the model.[2]

where:

CWU_j is the consumptive water requirements for rotation (j) as estimated by EPIC;

X_{ij} is the activity level of rotation j in PA (i);

b_{ik} is the amount of water applied adjusted for conveyance and application losses for irrigation system (k) in PA (i); and

WA_{ik} is the activity level of the irrigation system (k).

Dependable groundwater availability: The dependable groundwater constraint is:

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[1]A rotation is defined as a crop sequence used on a given land group under a given conservation and tillage practice.

[2]The irrigation system in the model include three for ground and three for surface. 1 = center pivot, 2 = hand move, 3 = mechanical move, 4 = gated pipe, 5 = ditch with siphon tubes, and 6 = flood.

			B	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	P12	P13
				IRROT1	IRROT2	Groundwater Application: Center Pivot	Hand Move	Mech. Move	Surface Water Application: Gated Pipe	Ditch	Flood	Water Depl.		Dry Irr. Conv.	Irr. Land Conv.	Dry Land Conv.
		C		C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}	C_{19}		$C_{1,10}$	$C_{1,11}$	$C_{1,12}$
Water requirement	L	R01	0	a	a	$-b_{33}$	$-b_{34}$	$-b_{35}$	$-b_{36}$	$-b_{37}$	$-b_{38}$					
Dependable ground-water available	L	R02	GW			1	1	1				-1				
Water depletion	L	R03	D									1				
Surface availability	L	R04	SW						1	1	1					
Land 1-Irr.	L	R05	IL1	1										-d	-f	
Land 2-Irr.	L	R06	IL2		1									-e	-g	
Land 1-Dry	L	R07	DL1											d		-h
Land 2-Dry	L	R08	DL2											e		-i
Pot. Irr. Land	L	R09	PIL1												1	
Pot. Dry Land	L	R10	PDL2													1
Dry Irr. Conv.	L	R11	DIC											1	-1	
Yield	G	R12	DMD	Y	Y											
Other inputs	L	R13	INP	J	J											
Soil loss	N	R14		G	G											

Figure 1. A schematic of a proposed water sector.

$$\sum_{k=1}^{3} WA_{ik} - WDT_i \leq GW_i \qquad (2)$$

where:

WA_{ik} was previously defined;

WDT_i is the level of the water depletion transfer activity in PA (i); and

GW_i is the quantity of dependable ground water supply.

Water depletion constraints: The water depletion constraint simply states that only a certain amount of water can be used through depletion of the aquifer.

Surface water availability: The functional form of the surface water availability constraint is:

$$\sum_{k=4}^{6} WA_{ik} \leq SW_i \qquad (3)$$

where SW_i is the quantity of surface water available for agricultural purposes.

The Objective Function

As illustrated in Figure 1, costs are incurred with the irrigation rotations, water application, and water depletion. The irrigation rotations' costs include the cost of input other than water application plus fixed costs associated with water application. The water application activities have a cost ($C_{1,3}$-$C_{1,8}$) that reflect the variable cost of the irrigation system assuming an average pumping depth per PA and other related variables expounded upon later in this paper. The water depletion activity objective function value reflects the cost of lifting water from an additional depth with depletion of the groundwater.

II. OVERVIEW OF IRRIGATION IN THE UNITED STATES

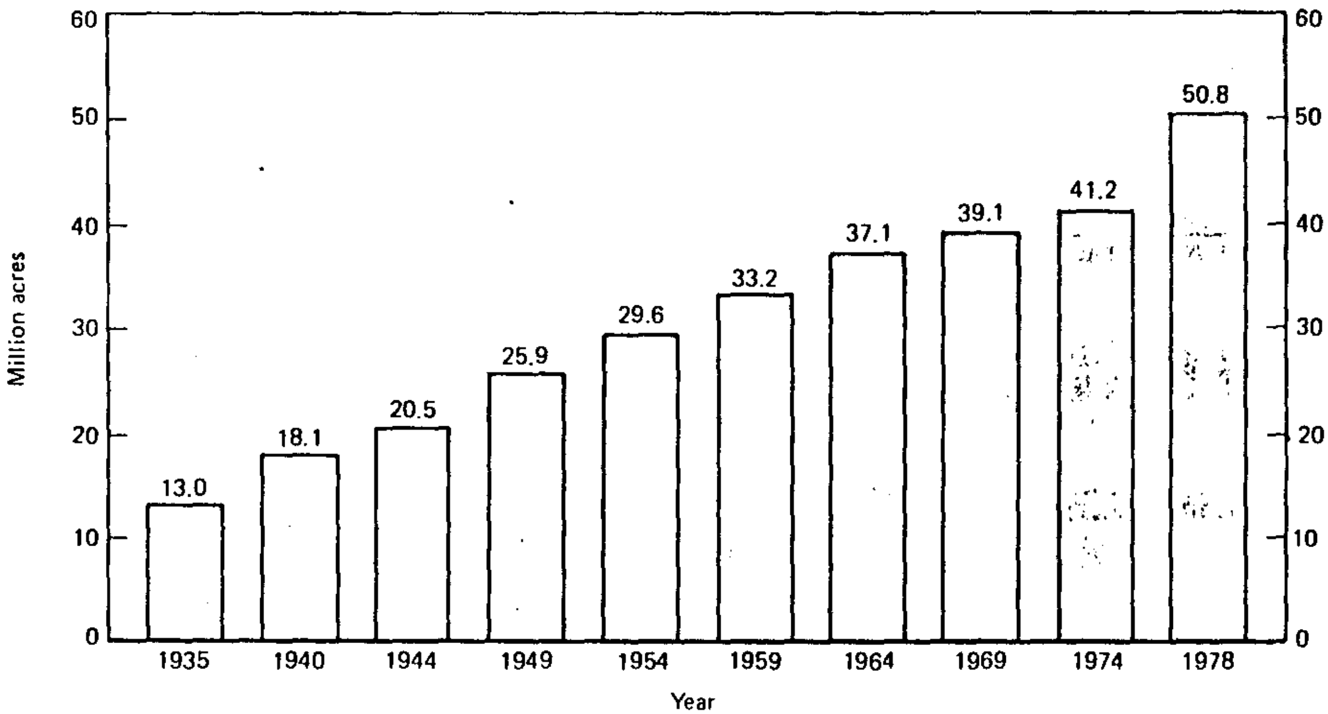
The 1978 Census of United States Agriculture reported 50.8 million irrigated acres. This is a 9.6 million acre increase over the reported 1974 acreage and the continuance of the irrigated acres trend (Figure 2). The irrigated acreage reported in the census is nearly 10 million acres less than the acreage reported in the Irrigation Journal. Three sources of the discrepancy are: the definition of a census farm will exclude some small holdings, the Irrigation Journal reports nonfarm irrigation such as golf courses and turf grass acres, and reporting and sampling error in each of the totals.

The largest percentage increase in irrigated acres from 1974 to 1978 was in the eastern states. The acreage increase was largest in the western states. Table 2 aggregates irrigation acres into the ten USDA regions. The growth of irrigated acres in the Corn Belt, the Lake States, the Southeast, and the Delta States does indicate the growing importance of irrigation in these regions.

While the growth of irrigation is slower in the western states, irrigation is vital to agriculture in this area. Figure 3 shows the percentage of total cropland irrigated in each state. The effect of water supply and irrigation costs will have a major impact on production in states with a high proportion of cropland in irrigation.

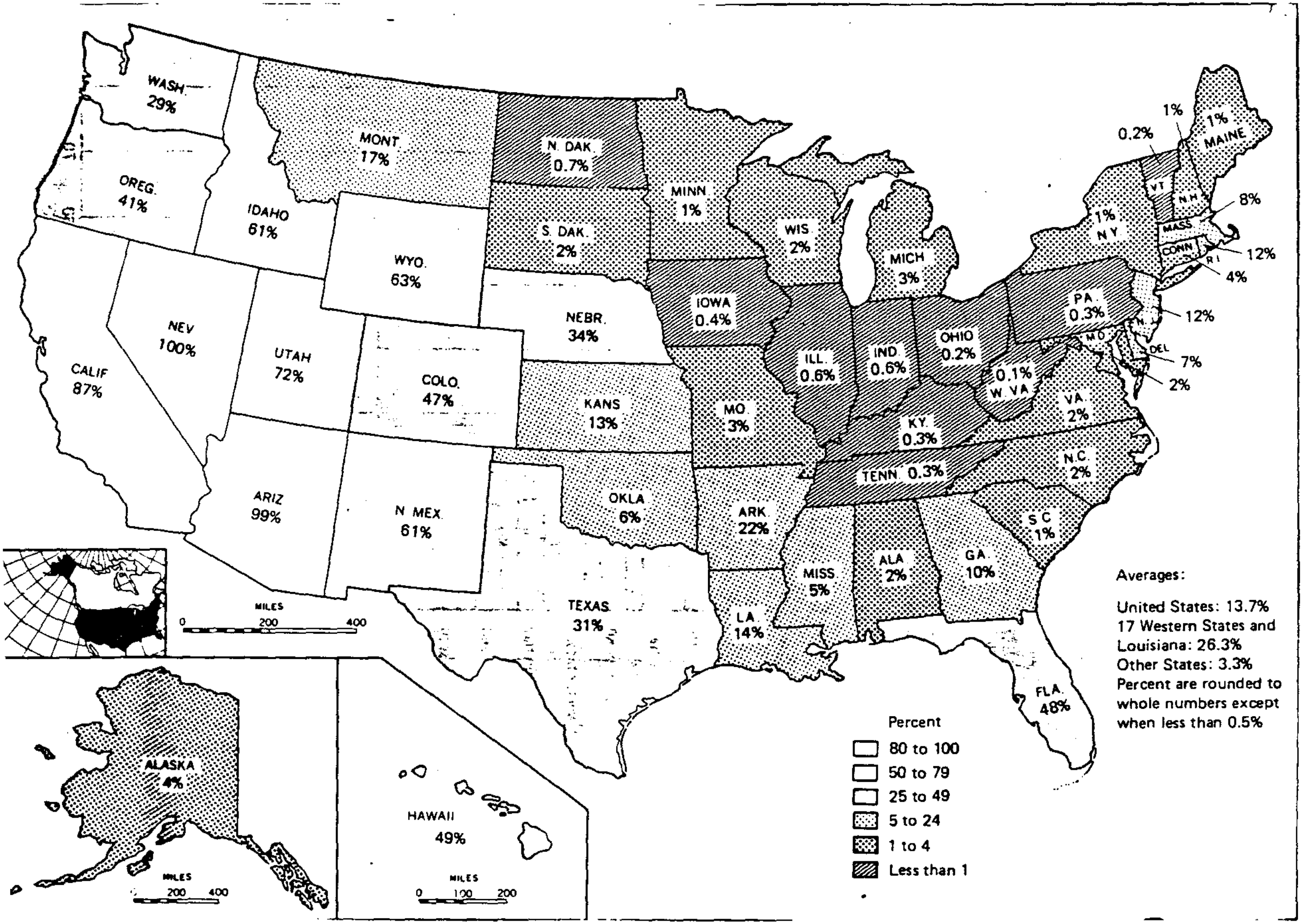
Acres Irrigated: 1935 to 1978

(1935, irrigated cropland harvested; 1940, acreage of irrigated cropland harvested and/or irrigated pasture; 1944 to 1978, acreage of irrigated land)



Source: U.S. Department of Commerce, 1978 Census of Irrigation

Figure 2. Acres Irrigated, 1935-1978



Source: U.S. Department of Commerce, 1978 Census of Agriculture

Figure 3. Percent of Cropland Irrigated by State.

Table 1. Irrigated acres - 1974 and 1978

Region and states	1974	1978	Percent Increase
Northeast			
(CT,DE,ME,MD,MA,NH,NJ NY,PA,RI,VT)	241,315	248,942	3.2
Lake States (MI,MN,WI)	302,543	482,663	59.5
Corn Belt (IL,IN,IA,MO,OH)	299,140	676,324	126.1
Northern Plains (KS,NB,ND,SD)	6,200,409	8,866,081	43.0
Appalachia (KY,NC,TN,VA,WV)	101,890	167,148	64.0
Southeast (AL,FL,GA,SC)	1,695,250	2,546,165	50.2
Delta States (AR,LA,MS)	1,812,108	2,677,874	47.8
Southern Plains (OK,TX)	7,108,963	7,620,614	7.2
Mountain (AZ,CO,ID,NV, NM,MT,UT,WY)	12,719,637	14,936,518	17.4
Pacific (CA,OR,WA)	10,619,165	12,205,305	14.9

Source: U.S. Department of Commerce, 1978 Census of Agriculture.

The major irrigated crop is corn. Approximately 17 percent of the irrigated acres are in corn. Alfalfa hay makes up 12 percent, and cotton nine percent of the irrigated acres. Six percent of the irrigated land is in orchards, six percent in wheat, and six percent in rice. The remaining crops are less than five percent of the total irrigated acres in the United States.

Sources of Water

Water can be divided into surface and ground sources. Groundwater is applied in proximity to the well from which the water is pumped. There is very little transfer of groundwater to localities that do not have groundwater. Forty percent of the water withdrawals for irrigation was from ground sources in 1980 [U.S. Geological Survey, 1980]. Surface water is obtained from lakes, streams, rivers, and drainage ways. The majority of surface water used in irrigation is conveyed through an intricate system of channels and lifting stations to deliver the water to the users.

The states of California, Nebraska, and Texas withdraw one-half of the total groundwater irrigation withdrawals. Groundwater accounted for over 50 percent of the irrigation water in Arizona, Arkansas, Florida, Illinois, Indiana, Iowa, Kansas, Minnesota, Mississippi, Missouri, Nebraska, New Jersey, Oklahoma, Texas, and Wisconsin. Other states where groundwater is prominent are California, Colorado, Idaho, Louisiana, and New Mexico. Irrigation with groundwater is localized because of the need to have a plentiful supply of water in the ground. Large aquifers, such as the Ogallala, facilitate the irrigation of large contiguous areas. Smaller aquifers and variable water supplies results in a sporadic pattern of groundwater irrigation. The long term viability of groundwater irrigation depends on the rate at which the aquifers are being depleted and total water supplies in the aquifer.

Surface water deliveries are handled by irrigation organizations. The 1978 Census of Irrigation Organizations defines an irrigation organization as any group of individuals, a company, a government district or agency, an individual that operates an irrigation supply system that delivers water to two or more farmers, or any organization which provides storage facilities for water ultimately used in irrigation. This definition includes incorporated and unincorporated mutuals, the U.S. Bureau of Reclamation constructed and operated and/or constructed and user operated projects, the U.S. Bureau of Indian Affairs, state and local governments, commercial companies, and others. The majority of water delivered to farms is by mutuals and districts. The U.S. Bureau of Reclamation constructed and user operated projects also deliver a high percent of total water to farms and ranches. Very little water is delivered by the U.S. Bureau of Reclamation constructed and operated projects, the U.S. Bureau of Indian Affairs operated projects, state and local governments, commercial companies, or others.

Irrigation Methods

The application of irrigation water can be broadly categorized into sprinkler, flood, and other. Sprinkler systems include center pivot, hand move, wheel move/side roll, solid set, traveller, and gun. The capital cost and operation costs of these systems are quite different. The sprinkler systems in use in 1978 were 47.0 percent center pivot, 27.5 percent mechanical move (wheel move, traveller, and gun), 20.2 percent hand move, and 5.3 percent solid set. Sprinkler systems irri gated 18.4 million acres in 1978, or 36.7 percent of total irrigated acres.

Gravity flow systems were used to irrigate 31.2 million acres (62.2 percent) in 1978. The 1978 Census categorized flood irrigation methods by gated pipe, ditches with siphon tubes, flooding using underground pipe with valves, and other flooding. The percent of gravity irrigated acres in each of these categories are 26.9, 27.7, 6.8, and 38.6, respectively.

The remaining category includes drip or trickle irrigation and subirrigation. There were .6 million acres (1.2 percent) irrigated by these methods in 1978. California and Florida accounted for 80 percent of the drip/trickle and subirrigation.

Energy Sources for Irrigation

Energy sources for irrigation are electricity, natural gas, LP gas, diesel fuel, and gasoline. The mix of these energy sources varies among regions in the United States. The west primarily uses electricity. The northern plains and midwest use electricity and diesel fuel. The south uses natural gas, LP gas, and electricity. The southeast uses diesel fuel, electricity, and gasoline. The Appalachia and northeast areas use diesel fuel and gasoline.

The energy costs for irrigation in 1978 were $408.9 million for electricity ($21.44/acre), $154.7 million for natural gas ($20.83/acre), $34.8 million for LP gas ($15.39/acre), $98.3 million for diesel fuel ($16.19/acre), and $6.2 million for gasoline ($17.95/acre). The per acre costs are a reflection of the volume of water applied, not the relative costs of the energy sources. The areas applying high water volumes use electricity and to a lesser extent natural gas. Gasoline is used only on low volume applications.

Laws and Institutions

Water use, and hence irrigation, is affected by the laws and institutions that regulate water use.[1] The doctrine of riparian rights governs water use in the eastern states and is retained to a lesser degree in California, Oregon, and Washington. The doctrine allows reasonable use of water to those landholders along the body of water, provided no major inconvenience is caused to other riparian users. The riparian doctrine was inadequate to deal with the drier west where water was often diverted great distances from the water source. The doctrine of prior appropriation evolved which encouraged and safeguarded private investments in water diversion. The prior appropriation doctrine recognizes the first to make beneficial use of the water as having the right to similar amounts of water from that stream. The prior appropriation doctrine was adopted in the 17 western states, including California, Oregon, and Washington.

Groundwater use was originally governed by the doctrine of absolute ownership because the pumping by one individual was perceived to

[1]U.S. Water Resources Council. The Nation's Water Resources 1975-2000, Volume 2: Water Quantity, Quality, and Related Land Considerations, Second National Water Assessment, Dec. 1978, p. 117.

have little influence on others. Texas is the only state to retain the doctrine of absolute ownership. Nebraska and California have adopted a reasonable use doctrine. The remaining western states employ a form of the prior appropriation doctrine to groundwater use.

The water laws, while providing a means of water allocation, can be a source of inefficient water allocation. The tying of water rights to land, as in the riparian doctrine, prevents the transfer of water to a higher value use. The vagueness of "beneficial use" does not imply an efficient allocation and may even perpetuate wasteful water uses. There is often little or no incentive to increase water use efficiency because the water saved cannot be used on other lands owned by the individual or the water saved may go to a senior appropriator when water supplies are short. These are a few illustrations of how the laws and institutions can inhibit the efficient allocation of water.

There are a number of treaties and compacts that affects the quantity of surface water that can be extracted from a river basin. There are a number of treaties with Canada and Mexico that affect water flows.[2] The treaties that primarily affect irrigation are: (1) flows into the St. Mary River and from the Milk River, (2) flows in the Rio Grande, and (3) flows from the Colorado River. Compacts are agreements among states for water diversions, flows, quality, and flood control. The compacts in the western states are primarily concerned with river flows from state to state.[3]

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[2]U.S. Water Resources Council, Ibid., p. 121.

[3]U.S. Water Resources Council, Ibid., p. 124.

III. WATER SUPPLY

Surface

The most complete evaluation of water availability in the United States was compiled by the U.S. Water Resources Council in their Second National Water Assessment (SNWA). We cannot say that this information source is perfect for our needs. Areas where the SNWA data trouble us most include:

a) Lack of information on groundwater availability. Though we know areas where fresh groundwater is being depleted, we don't know how long this can continue at various consumption rates.

b) Assessed total streamflow includes groundwater withdrawals. This creates a problem in that groundwater withdrawals for irrigation are endogenous to our model so we don't want to consider groundwater withdrawals as a part of streamflow.

c) Since the completion of the SNWA more data on water use has become available. Inconsistencies in water use and projected use in the SNWA with data from the USGS 1980 survey gives rise to caution in the use of the data set chosen.

For each PA, Table IV-4 of the SNWA has the Current Streamflow Supply (CSS). Quantities are given in million gallons daily (mgd) but conversion to acre feet will be easier if done after further data manipulation. These quantities are given for "dry" conditions meaning drought conditions which may occur in one of every five years. Not all water in CSS is surface water. CSS is the streamflow that would occur if consumption were eliminated, groundwater withdrawals were continued, and if "1975" water transfers continued.

Some groundwater withdrawals occur from the exogenous consumption components, the nonagricultural uses. Since we will use the SNWA's projection for consumption from the nonagricultural components, where the water comes from will be of little circumstance. Exogenous consumption quantities are given in Table IV-3 (SNWA) for steam-electricity, manufacturing, domestic central and noncentral, commercial and minerals. Projections of these are given for 1985 and for the year 2000. (For more information on these components of water demand, see Volume 1, p. 32-41, SNWA.) Exogenous consumptive demands must be subtracted from CSS.

The groundwater used in agriculture is considered part of CSS. As mentioned before, this component must be taken out. The SNWA does not give groundwater use in agriculture but does give total groundwater withdrawals. By using the 1980 USGS Water Survey data, a ratio of groundwater withdrawn in agriculture for irrigation to total groundwater withdrawn can be determined. Assuming the ratio derived from the USGS survey data approximates the relationship of groundwater use in the SNWA, then we can multiply this ratio by total groundwater withdrawn (Table III-1, SNWA) to get an estimate of groundwater used for irrigation in agriculture. This quantity of water must be subtracted from CSS.

As an estimate of instream water needs, we will assume it to be 30 percent of average flow. At this level good survival habitat for most aquatic life forms will be maintained (see SNWA, Volume 2, p. 45). Habitat needs are used as an estimate since, "In all subregions, the fish and wildlife use is one dominant instream flow use" (SNWA, Volume 2, p. 34). To get 30 percent of average flow one begins with Assessed Total Streamflow (ATS) (Table III-5, SNWA) for base conditions. Base conditions define average flows. ATS includes water transfers and groundwater withdrawals both of which must be considered in establishing instream flow needs.

Water exports and imports are given in Table III-2 of the SNWA. By adding exports to and subtracting imports from ATS, water transfers will be accounted for.

ATS was used for estimating the instream use requirement since it is less than CSS by the level of groundwater depletion. To subtract out all groundwater would underestimate the instream use requirement since some portion of the groundwater withdrawn would have made its way to surface supplies had there been no withdrawals. The SNWA states that some streams in the arid southwest may be totally spring fed during the dryest months. A 70 percent depletion of streamflow is a liberal estimate for consumptive use. The Maximum Instream Use (MIU) given in the SNWA seems too conservative since Assessed Surplus Streamflow is negative for many of the PAs. Therefore, 30 percent of ATS corrected for water transfers will estimate the minimum instream use requirement.

Six PAs must meet outflow requirements as given by treaties and compacts, Table III-3, SNWA. To ensure that they do, the instream use requirement must be compared to treaties and compacts and the larger volume selected as the new instream use requirement.

Instream use requirement must also be subtracted from CSS to determine the water available to agriculture.

Summarizing what has been done so far then:

CSS --	current stream supply	
minus nonagricultural uses --	exogenous consumption	
minus GW in agriculture --	groundwater used in agriculture	
minus instream use --	also accounts for treaties on compacts	
equals SW --	surface water available to agriculture for beginning PAs	(4)

For PAs which receive no streamflow from other PAs, SW will be the maximum surface water available. Downstream PAs must subtract not only their quantities of nonagricultural uses and GW in agriculture but must also subtract all upstream PAs quantities from CSS.

So now we have:

$$\text{CSS} - \Sigma \text{ nonagricultural uses} - \Sigma \text{ GW used in agriculture} - \Sigma \text{ Instream use} = \text{SW} \quad (5)$$

where Σ stands for "the summation of"; the summation will be of all upstream PAs and the current PA being evaluated.

Not all agriculture water consumption will be endogenous. Those which are exogenous must also be subtracted from CSS before surface water supply can be determined for each PA. To explain more on exogenous agricultural water demands, we quote from CARD report 107T;

> "The water right-hand-sides represent the quantity of water required for exogenous crop and livestock prodction. The projected irrigated acres producing exogenous crops provided by NIRAP are used in conjunction with water use coefficients developed by the Special Projects Division (1976) of the Soil Conservation Service to estimate the quantity of water required to produce the exogenous crops in the irrigated PAs.
>
> The exogenous determination of livestock water demands is derived from several sources. Projected livestock production by state is estimated through the NIRAP system. These state projections are weighted from states to the PAs with weights derived from the 1974 Census of Agriculture (Bureau of the Census, 1977). Production by producing area is then multiplied by water consumption factors developed by the Agricultural Resource Assessment System Technical Committee (1975). These coefficients, presented in Boggess, are then summed with the water required for irrigated exogenous crops to form the water right-handsides."

For more information, see the cited report.

To project water supplies available to agriculture for 1985 and 2000, only three items are of concern. First, we need to see if water exports or imports changed from 1975 levels (Table III-2, SNWA). Increases in exports (import decrease) must be subtracted from and decreases in exports (import increases) must be added to CSS. Second, increase in nonagricultural consumptive demand for water must be subtracted out of (and decrease added in to) CSS. And, third, increases in exogenous agriculture demands need to be subtracted out of (decreases added in to) CSS.

Groundwater

As pointed out in the introduction, information on groundwater availability is very limited. The SNWA does not project future groundwater withdrawals given the lack of data.

Note that in Figure 4, all but 40 PAs do have groundwater overdraft occurring. For the areas where overdrafts occur, we can determine their recharge rate (the difference between groundwater withdrawn and overdraft; Table III-1 SNWA). Converting this value to acre-feet per year will give us dependable supply for groundwater to enter into Figure 1. In the 40 PAs where overdraft is not occurring, we know dependable supply must be at least as great as that quantity of groundwater currently withdrawn. A conservative dependable supply would use these values.

The amount of groundwater available to overdraft is not given in the SNWA. For many aquifers, economic exhaustion may occur before physical exhaustion whereby the physical supply does not become the constraint. The present rate of overdraft may be the best estimate for allowable annual overdraft. This value is listed in the SNWA, Table III-1 and after converting to acre-feet, will be entered as the final constraint in Figure 1.

Water Conveyance Efficiency

This section deals with the method employed in determining coefficients for conveyance efficiency by a producing area. Conveyance efficiency refers to the efficiency of a system in transporting water from the reservoir to the field boundary. In general, not all water will

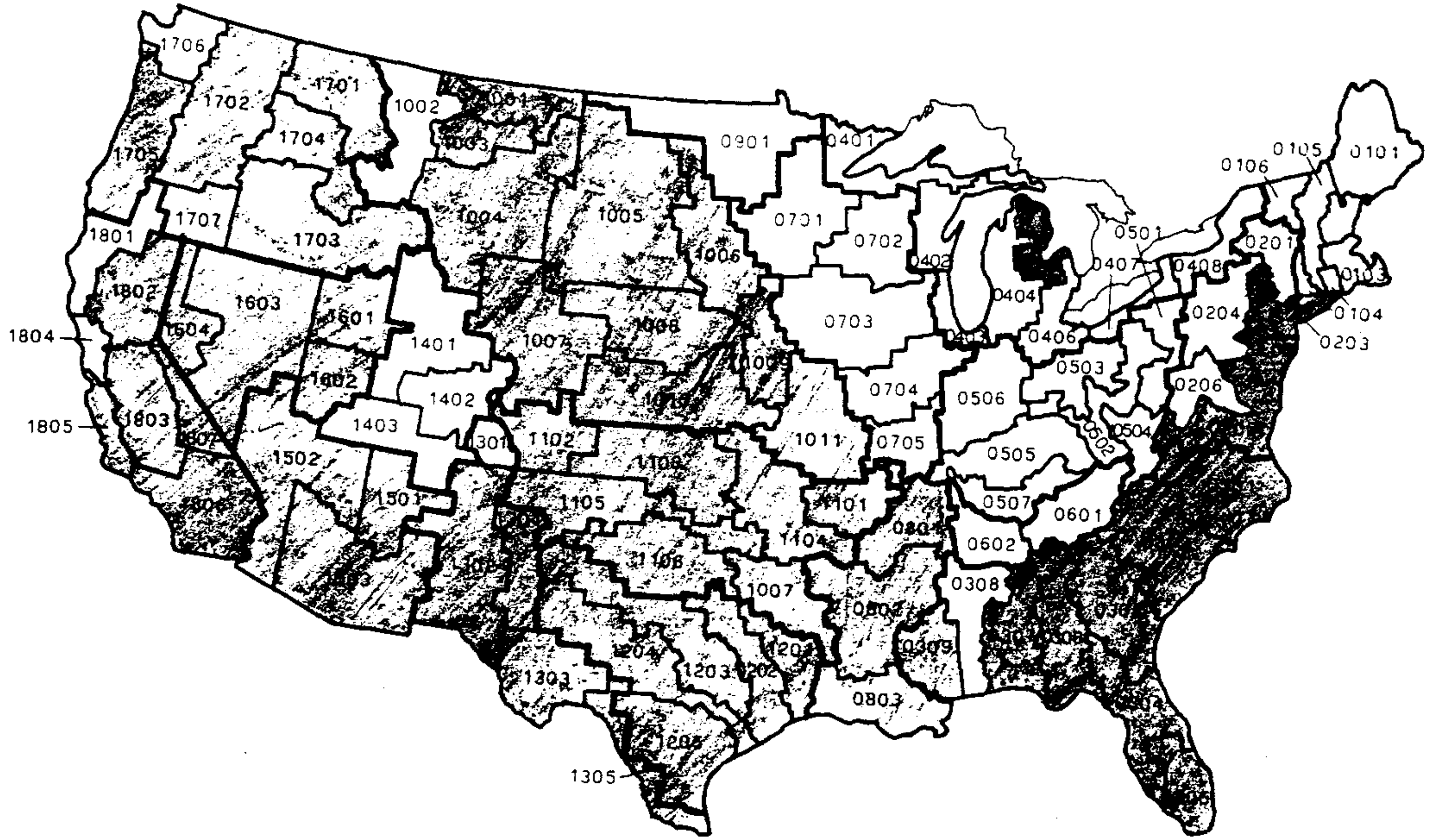

Figure 4. Water Resource Council's agregated subareas.

*Shaded areas are where groundwater overdraft is occurring.

reach the farm, as some losses are incurred due to seepage, evaporation, and transpiration of vegetation along the canal. This type of loss is referred to as conveyance loss. Conveyance efficiency is broken down into two types -- groundwater and surface water. Conveyance efficiencies are in general positive and less than one, reflecting the fact that some loss is generally incurred in the conveyance process.

Groundwater and surface water conveyance efficiencies will determine the b_{ij} coefficients in the model (see Figure 1). These coefficients can be interpreted as the proportion of an acre foot of withdrawn water that is available for application to the field. That is, for each acre foot of dependable groundwater or surface water available, some portion, b_{ij}, will actually be conveyed to the farm and will be available for application. Thus, complete, realistic estimates of conveyance efficiency are important to this model.

However, determining conveyance efficiency proved to be a difficult task for us, due to the lack of complete, consistent data. In attempting to compute conveyance efficiencies, we tried three approaches, none of which successfully yielded realistic, complete results.

Our original approach was to use information obtained from the SCS publication "Crop Consumptive Irrigation Requirements and Irrigation Efficiency Coefficients for the United States" in conjunction with information provided by the U.S. Geological Survey. The SCS defines conveyance efficiency as "The efficiency of the system that conveys the irrigation water from the diversion point to the boundary of the using town." Conveyance efficiencies are broken down by state, aggregated subarea, and subarea. There are three efficiency levels given -- those for 1975, 2000, and high efficiency (best management practices). Conveyance efficiency figures were computed by the SCS as the sum of groundwater and surface water, each weighted by their respective conveyance efficiencies. Groundwater is assumed by the SCS to have an efficiency of 100 percent, or 0 percent conveyance loss. Surface water is generally less than 100 percent. However, as the SCS figures were a weighted sum of the two, it was necessary to break them down to obtain surface water efficiencies. In order to do this, we used figures for ground- and surface water withdrawn by state, aggregated subarea (ASA) and subarea (SA) obtained from the USGS. The formula used was as follows:

$$SWE = \frac{CE - (GW \cdot GWE)}{SW} \qquad (6)$$

where SWE = surface water efficiency (percent);

CE = conveyance efficiency (percent);

GW = percentage of groundwater within a subarea;

GWE = groundwater efficiency (always equal to 1.0); and

SW = percentage of surface water within a subarea.

However, in the process of computing this data, we arrived at several unrealistic figures (see Table 2). This is likely due to the difference in time between the data sets. The SCS publication was released in 1976, while the USGS information was from 1980. As the in formation used by the authors of the SCS publication was unavailable to us, and was likely to be too dated for us to use, we attempted another approach.

Our second approach was an attempt to use information from the 1978 Census of Agriculture. The Bureau of the Census defines conveyance losses as "... water losses due to seepage or evaporation after water enters the organizations conveyance facilities." We took the ratio of conveyance losses to net water supply to disposition obtained from Volume 4 (Irrigation), Chapter 2, Table 7 (Net Water Supply, Disposition, and Exchange between Irrigation Organizations). This ratio was then subtracted from one to arrive at the conveyance efficiency. However, this method proved to be unworkable, as much information was missing due to confidentiality, lack of irrigation organizations within a subarea, or both (see Table 2).

Finally, we attempted to compute conveyance efficiency by using the second methodology, but with figures on conveyance loss and surface water withdrawn obtained from the USGS. The USGS defines conveyance loss as "Water that is lost in transit from a pipe, canal, conduit, or ditch by leakage or evaporation." Again, the results yielded some unrealistic figures (see Table 2). This occurred because at times the conveyance loss figures were greater than the surface water withdrawn figures. It is unclear at present as to why this is so, but an explanation is being sought.

Thus, despite several attempts, no workable methodology has been found. The basic problems are (1) Time discrepancies between data

Table 2. Conveyance efficiencies obtained from the various approaches

PA	SCS1	SCS2	CENSUS	USGS
48	0.50	0.50	*****b	0.77122
49	0.50	0.50	*****b	0.77121
50	0.50	0.50	0.82670	0.77121
51	0.50	0.50	*****b	0.64609
52	0.90	0.89	*****b	0.72824
53	0.99	0.89	*****b	0.44086
54	0.74	0.65	0.71288	0.68104
55	0.90	0.63	*****b	0.39181
56	1.00	1.00	*****b	-0.70313d
57	0.96	0.60	*****b	0.37594
58	0.95	0.58	*****b	0.33374
59	0.98	0.50	*****b	-1.57839d
60	0.97	0.96	*****b	0.93373
61	0.97	0.67	*****b	0.60000
62	0.64	0.58	0.85026	0.85004
63	0.99	0.75	*****b	0.90583
64	0.98	0.95	*****b	0.95294
65	0.90	0.33	*****b	0.98146
66	1.00	1.00	*****b	1.00000
67	1.00	1.00	*****b	-0.31579d
68	0.94	0.73	*****b	0.46482
69	0.98	0.96	*****b	0.87595
70	0.91	0.92	*****b	0.82031
71	0.91	0.87	*****b	0.87413
72	1.00	1.00	*****b	0.81833
73	0.97	0.89	*****b	0.74225
74	0.90	-2.33a	*****b	0.92500
75	0.90	0.82	*****b	0.85507
76	0.98	0.97	0.80713	0.95007
77	0.68	0.56	0.81655	0.80003
78	0.80	0.70	0.89683	0.97290
79	0.88	0.65	*****c	0.90476
80	0.78	0.44	0.65245	0.97384
81	0.85	0.84	*****c	0.77169
82	0.73	0.72	*****c	0.84760
83	0.73	0.73	0.86698	0.90000
84	0.86	0.86	0.85434	0.92134
85	0.55	0.30	0.85518	0.83455
86	0.74	0.68	0.90827	0.82947
87	0.78	0.42	0.78435	0.68387
88	0.77	0.74	*****c	0.87085
89	0.79	0.65	0.83675	0.83408
90	0.97	0.96	*****c	0.74623

Table 2. Continued

PA	SCS1	SCS2	CENSUS	USGS
91	0.89	0.89	0.72973	0.67371
92	0.68	0.66	0.78181	0.77147
93	0.70	0.67	0.75940	0.74717
94	0.72	0.62	0.84119	0.66898
95	0.63	0.61	0.80935	0.74674
96	0.87	0.84	*****c	0.78023
97	0.80	0.78	*****c	0.85149
98	0.59	0.55	0.87438	0.68187
99	0.70	0.67	0.83989	0.79268
96	0.87	0.84	*****c	0.78023
97	0.80	0.78	*****c	0.85149
98	0.59	0.55	0.87438	0.68187
99	0.70	0.67	0.83989	0.79268
100	0.80	0.60	*****c	0.64176
101	0.80	0.60	0.88106	0.71063
102	0.75	-1.08a	*****c	-1.22766d
103	0.75	-1.50a	0.98489	-1.04667d
104	0.75	0.70	*****c	0.78131
105	0.75	0.07	*****c	0.50861

SCS1-Conveyance efficiencies weighted by ground and surface water (rough estimates by producing area).

SCS2-Surface water conveyance efficiencies obtained by first approach (rough estimates only).

CENSUS-Surface water conveyance efficiencies obtained by second approach.

USGS-Surface water conveyance efficiencies obtained by third approach.

a-Negative numbers due to timing discrepancy between data sets.

b-Data missing due to confidentiality, lack of irrigation organizations, or both.

c-Data missing due to confidentiality only.

d-Negative numbers due to conveyance losses exceeding surface water withdrawn.

SOURCES-Soil Conservation Service, U.S. Geological Survey, U.S. Bureau of Census.

sets; (2) Incomplete data sets; and (3) Consistency. These problems must be solved in order to obtain estimates for the b_{ij} coefficients.

IV. POTENTIAL IRRIGABLE ACRES

There are two factors that determine the potential irrigable acres. The first is the inherent characteristics of the land such as slope, permeability, salinity, wetness of the soil, etc. These characteristics determine the practicability of irrigating a tract of land. The 1977 National Resources Inventory (NRI) indicates that irrigation was practiced on all land classes, though acreages were low for the lower quality lands. Irrigated acres reported in the NRI for the eight land groups considered in this analysis, and the land subclasses in each land group, are reported in Table 3. Irrigation occurs within

Table 3. Irrigated acres by land group, 1977

Land group	Land classes (subclass)	Acres (1000)
I	I, IIwa, IIIwa	8,350
II	IIe	7,433
III	IIIe	5,802
IV	IVe	3,420
V	IIs, IIIs, IVs	13,003
VI	IIc, IIIc, IVc	3,073
VII	IIw, IIIw, IVw	12,041
VIII	V, VI, VII, VIII	2,671

each of the land classes - subclasses categories and as a result an irrigation component will be required for each land group.

The method of irrigation will be affected by the slope of the land. Gravity irrigation (gated pipe, siphon tubes, and flooding) requires a gently sloping field. The use of gravity systems could be constrained in the model by field slope. Sprinkler systems facilitate irrigation of fields with greater slope, but field slope could still be a constraining factor.

The second factor that will constrain the potential irrigable acres is the availability of water. Irrigation with groundwater is generally confined to an area in proximity to the well. Therefore, groundwater irrigation will be limited to those areas with an adequate supply of groundwater. Irrigation with surface water will be limited by the supply of surface water and by the water distribution system. Surface water projects service a limited number of acres, dictated by the canal system. A plentiful supply of surface water will not mean additional acres will be irrigated because the water may not be transportable to the areas not irrigated.

The model must have a limit on irrigable acres that takes these two factors into account. Irrigation systems could be constrained by land class characteristics. The water supply effect on potential acres needs to be addressed to prevent groundwater use in areas without groundwater and surface water use in areas where surface water can not be transported.

Irrigated acres by surface and groundwater can only be constrained directly by doubling the size of the CARD/RCA85 model. The present formulation of the model does not distinguish between surface and groundwater used in the rotation (Figure 1). The distinction of groundwater from surface water would require specifying both groundwater and surface water rotations. A possible approach to constrain the groundwater and surface water acres would be to constrain water use based on water use per acre and the potential irrigable acres.

V. ENERGY SOURCES AND EFFICIENCIES

The energy use in irrigation is required for the RCA analysis. The quantity of energy used per unit of irrigation will depend on the energy source and the efficiency of that energy source. Energy sources and efficiencies to the year 2030 are also required.

The fossil fuel requirements for irrigation include the direct use in internal combustion engines and the indirect use in electricity generation. The efficiency of electricity generation used in this study refers to the electric energy produced per unit of fossil energy used. Hydro and nuclear electricity generation will increase the efficiency because fossil fuels are replaced by nonfossil sources of energy. A second efficiency measure is the efficiency of the internal combustion and electric engines used in pumping water.

The efficiency of electrical generation in the future will depend on the relative supplies of different energy sources. A switch from oil and gas to coal or nuclear will affect electric energy generation efficiency. The development of new energy sources such as geothermal, nuclear fusion, and solar will also affect the efficiency of electricity generation.

The proportion of energy sources in generating electricity vary by region. The percent of electricity generated by source is given in Table 4 for the ten USDA regions in the conterminous United States for 1981. The regions are the same as those indicated in Table 2.

Table 4. Distribution of electric utility net generation, by region, 1981

Region	Coal	Oil	Gas	Nuclear	Hydro	Other
1	6.1	54.6	---	33.3	6.1	---
2	15.0	31.7	13.3	21.7	18.3	---
3	74.1	7.8	.9	16.4	.9	---
4	65.2	10.5	4.8	15.2	4.3	---
5	78.9	2.2	1.1	16.8	1.1	---
6	33.1	1.3	61.6	2.7	1.3	---
7	83.3	---	6.2	8.3	2.1	---
8	76.1	---	2.2	---	21.7	---
9	19.3	18.1	38.6	1.2	20.5	2.4
10	5.9	---	1.5	5.9	86.8	---

Source: U.S. Department of Energy, 1982.

The availability of oil, gas, and desirable hydro electric sites will change the composition of inputs to generate electricity. National projections to the year 2030 are for an increased importance in nuclear and geothermal sources to generate electricity [U.S. Forestry Service, 1981]. Table 5 contains the source percentages projected for electricity generation.

The fossil fuel efficiency in electric energy generation is defined on the electric energy generated divided by the energy required to generate the electricity. Table 6 contains the electricity generated, the estimated energy used, and the efficiency of electric generation by U.S.D.A. region for 1981.

The high efficiency for region 10 is because only a small percent of the electricity generated is from fossil fuels. Hydro is the major

Table 5. Projected primary electricity input percentages

Year	1977	1990	2000	2010	2020	2030
Source:						
Coal	46.0	39.8	35.1	38.1	40.3	38.2
Oil	17.0	19.3	10.3	6.7	4.7	3.5
Gas	14.7	0	0	0	0	0
Nuclear	12.1	27.2	35.3	33.1	28.8	26.5
Hydro	11.1	10.5	9.4	7.7	6.6	5.3
Geothermal	0	2.6	8.8	12.3	16.1	21.0
Other	0	.6	1.1	2.0	3.5	5.5
Net Generation (Quads/yr)	7.3	10.9	14.2	18.5	22.9	28.0
Available Electricity	6.6	9.9	12.9	16.8	20.9	25.4

Source: U.S. Forestry Service, 1981.

Table 6. Electric energy generated, energy use, and efficiency for 1981 by USDA region

Region	KWH generated (10^9)	BTU used (10^{12})	Efficiency (%)
1	76.8	512.8	51.1
2	137.0	889.2	52.5
3	266.4	2,266.7	40.1
4	482.6	3,839.9	42.9
5	421.6	3,807.1	37.8
6	343.5	4,003.1	29.3
7	112.1	1,205.2	31.7
8	104.3	1,034.3	34.4
9	192.7	1,574.4	41.7
10	155.7	141.2	376.0

Sources: U.S. Department of Energy, 1982, and the National Coal Association, 1974 source of electricity generation in this region. Note that the efficiency measure encompasses all electricity, not just the electricity generated from fossil fuels.

The prices of alternate energy sources are projected in the FOSSIL79 report [U.S. Forestry Service]. The projected prices are in Table 7. The projections are for large increases in natural gas

Table 7. Projected energy prices

	(1980 $/mBtu)					
	1977	1990	2000	2010	2020	2030
Natural gas						
Delivered price		6.27	8.66	11.75	17.35	12.52
Wellhead price	.99	3.86	5.05	10.62	16.22	11.39
Petroleum						
Delivered price		10.53	14.09	16.33	18.95	18.95
Wellhead price	2.40	7.67	11.23	13.48	16.09	7.91
Coal						
Delivered price		1.95	2.02	2.19	2.47	2.58
Mine price	1.14	1.24	1.24	1.33	1.51	1.52
Electricity						
Delivered price	12.72	19.50	17.68	17.30	16.36	14.85

Source: U.S. Forestry Service, 1981.

and petroleum prices. The delivered prices of natural gas and petroleum are projected to double from 1990 to the year 2030. Delivered coal prices are projected to increase by 32 percent and electricity prices to decline over this same time period.

The price projections in Table 7 would indicate a major shift in energy use to electricity. A relative price decline of this magnitude would result in many stationary energy uses switching to electricity and the development of technologies to use electricity rather than oil and gas. Irrigation pumps should be electric by the year 2030. The unavailability of electricity as a source of irrigation energy would likely make irrigation unprofitable at these prices.

VI. IRRIGATION PUMPING AND EFFICIENCIES

Energy requirements for irrigation include lifting surface and groundwater to the field, and pumping the water through the field distribution system. The energy required to apply a specified quantity of water will be a function of the surface and groundwater lifts, the application system, the overall pumping unit efficiency, and the distribution of energy sources used in pumping. The energy required by producing area for irrigation can be expressed in the following equation:

$$ER_i = f(GL_i, SL_i, PE_i, WE_i, GW_i, SW_i, ME_j, WP_{ij}, SH_i, WS_i, EE_i) \quad (7)$$

$i = 1, \ldots, 105$ for the producing areas s(PAs).

$j = 1, \ldots, 5$ for the five major power sources: electric, gasoline, diesel fuel, LP gas, and natural gas.

where:

ER_i is the energy required to obtain and apply one acre-foot of water in the ith PA,

GL_i is the average pumping depth for groundwater in the ith PA,

SL_i is the average feet of lift for surface water in the ith PA,

PE_i is the water pump efficiency in the ith PA,

WE_i is the surface water conveyance efficiency in the ith PA,

GW_i is the proportion of total water use from groundwater in the ith PA,

SW_i is the proportion of total water use from surface water in the ith PA,

ME_j is the mechanical efficiency of the jth power source,

WP_{ij} is the proportion of the jth power source in the ith PA,

SH_i is the average static head for sprinkler application in the ith PA,

WS_i is the proportion of irrigated acres having water applied by sprinklers in the ith PA, and

EE_i is the efficiency of converting fossil fuel to electricity in the ith PA.

Equation 7 is specified in aggregate for the producing area. The effect of different pump size, power unit size, pumping depth, pumping depth throughout the season, etc., within a PA are not taken account of explicitly. The data required for individual pumping unit energy requirements are too immense for this study.

Pump Lift

The pump lift for groundwater is a yearly average of the pumping depth. Pumping depths for groundwater are determined on the reported depth of 339,581 wells in the United States [U.S. Department of Commerce, 1982]. The well depths are reported by water resource area (WRA) for areas where irrigation is minor, and are reported by aggregate subarea (ASA) where irrigation is of major importance. The surface water lift is obtained from a survey of irrigation organizations [U.S. Department of Commerce, 1982]. The average lift is reported for the 17 Western States, the Lower Mississippi, and the South Atlantic - Gulf regions. Surface water use in the remaining areas of the conterminous United States is not large. Surface water is primarily pumped directly from the source to the distribution system in these remaining areas.

The groundwater pumping depth reported by ASA has to be specified by PA. There is a direct ASA to PA correspondence for most of the PAs. Where an ASA is broken down into two PAs, the pumping depth was weighted to PA based on the depths reported by Dvoskin. The surface water lifts reported in the Census are broken into the initial lift from the water source and the subsequent lifts required to move the water to the fields. These two values were combined to obtain the average lift for surface water by PA.

The data on groundwater and surface water lift are presented by PA in Table 8. The groundwater data includes water depth, pumping depth, well depth, and average pumping capacity.

Table 8. Average ground- and surface water lift

Producing region	Water Depth (ft)	Pumping Depth (ft)	Well Depth (ft)	Capacity (gpm)	Surface lift (ft)
1	26.	82.	114.	319.	
2	26.	82.	114.	319.	
3	26.	82.	114.	319.	
4	26.	82.	114.	319.	
5	26.	82.	114.	319.	
6	26.	82.	114.	319.	
7	29.	71.	112.	475.	
8	29.	71.	112.	475.	
9	29.	71.	112.	475.	
10	29.	71.	112.	475.	
11	29.	71.	112.	475.	
12	29.	71.	112.	475.	
13	29.	54.	91.	574.	9.
14	50.	91.	248.	614.	9.
15	91.	159.	301.	724.	9.
16	52.	98.	313.	626.	9.
17	27.	47.	116.	899.	9.
18	27.	47.	116.	913.	9.

Table 8. Continued

Producing region	Water Depth (ft)	Pumping Depth (ft)	Well Depth (ft)	Capacity (gpm)	Surface lift (ft)
19	27.	47.	116.	913.	9.
20	27.	47.	116.	913.	9.
21	27.	47.	116.	913.	9.
22	33.	74.	114.	1,013.	
23	33.	74.	114.	1,013.	
24	33.	74.	114.	1,013.	
25	33.	74.	114.	1,013.	
26	33.	74.	114.	1,013.	
27	33.	74.	114.	1,013.	
28	33.	74.	114.	1,013.	
29	33.	74.	114.	1,013.	
30	45.	78.	120.	513.	
31	45.	78.	120.	513.	
32	45.	78.	120.	513.	
33	45.	78.	120.	513.	
34	45.	78.	120.	513.	
35	45.	78.	120.	513.	
36	45.	78.	120.	513.	
37	59.	84.	102.	484.	
38	59.	84.	102.	484.	
39	30.	72.	124.	751.	
40	30.	72.	124.	751.	
41	30.	72.	124.	751.	
42	30.	72.	124.	751.	
43	30.	72.	124.	751.	
44	47.	89.	132.	1,133.	12.
45	36.	83.	123.	1,653.	11.
46	68.	125.	241.	1,218.	20.6
47	27.	76.	115.	677.	38.
48	157.9	201.2	294.	680.	36.1
49	86.	148.	289.	673.	61.8
50	148.1	188.7	275.9	680.	34.
51	8.	18.	22.	508.	68.7
52	89.	163.	228.	659.	90.1
53	19.	34.	48.	659.	40.
54	63.	97.	125.	816.	31.3
55	75.	137.5	218.8	933.	54.
56	45.	41.3	131.2	933.	54.
57	32.	67.5	114.4	828.	15.
58	96.	156.8	210.5	808.	31.
59	83.	135.2	181.5	808.	31.
60	42.4	90.5	153.6	828.	15.
61	38.	82.	132.	1,103.	64.
62	40.	73.	91.	755.	62.

Table 8. Continued

Producing region	Water Depth (ft)	Pumping Depth (ft)	Well Depth (ft)	Capacity (gpm)	Surface lift (ft)
62	40.	73.	91.	755.	62.
63	105.	166.	215.	755.	68.
64	38.	82.	132.	1,103.	68.
65	272.2	420.	522.6	711.	34.
66	125.8	194.	241.4	711.	34.
67	170.6	245.2	276.8	590.	68.
68	99.4	142.7	161.2	590.	68.
69	96.	143.	198.	516.	68.
70	92.2	198.1	262.3	765.	37.4
71	137.8	295.9	391.7	765.	37.4
72	208.	281.	318.2	504.	107.
73	128.	173.	195.8	504.	107.
74	132.	207.3	248.	460.	50.0
75	82.	128.7	154.	460.	50.0
76	160.	257.	577.	1,072.	33.
77	32.	84.	141.	1,002.	74.
78	83.	161.	255.	894.	29.
79	156.4	255.5	514.6	835.	15.
80	105.6	172.5	347.4	835.	29.
81	118.	196.	311.	1,248.	99.
82	18.	51.	65.	570.	52.
83	38.	91.	118.	1,104.	196.5
84	25.	77.	89.	491.	45.5
85	103.1	164.8	305.6	1,092.	216.
86	110.9	177.1	328.4	1,092.	66.3
87	195.	283.	527.	878.	91.5
88	101.	168.	314.	910.	138.
89	78.	139.	344.	1,150.	153.
90	52.9	110.5	251.3	1,278.	16.
91	83.1	173.5	394.7	1,278.	16.
92	59.	152.	212.	672.	140.
93	91.	150.	248.	645.	226.
94	156.	224.	339.	1,109.	221.4
95	75.	148.	267.	719.	91.
96	47.	85.	120.	315.	134.2
97	57.	143.	158.	319.	274.
98	42.	95.	262.	1,101.	80.
99	40.	92.	179.	774.	51.
100	58.	122.	260.	863.	41.7
101	102.	170.	319.	814.	115.5
102	77.	151.	237.	771.	204.
103	88.	144.	254.	748.	422.
104	115.	210.	373.	664.	495.
105	68.	141.	263.	893.	259.

Sources: U.S. Department of Commerce, 1982, Volumes 4 and 5.

The pumping depth for groundwater is greatest in the Southern Plains. Producing area 65 has the deepest pumping depth, over 400 feet. In addition, many of the PAs in Oklahoma, Texas, New Mexico, and Arizona have average pumping depths of almost 300 feet. Surface water lifts are highest in California. Producing area 104 has an average lift of 495 feet. The high lifts in California take into account the pumping plants in the California State Water Project, such as the A.D. Edmonston plant on the California Aqueduct with a static head of 1,926 feet [California Statistical Abstract, 1978].

Ground- and Surface Water

The supply of ground- and surface water used in irrigation varies greatly from one PA to the next. The proximity of the water source is a major determinant of whether irrigation is practiced. Groundwater is utilized at the location of extraction. Surface water is generally transported from the source to the use point through a system of canals Surface water is often transported long distances, such as in the California Aqueduct.

Forty percent of the water withdrawn for irrigation in 1980 was groundwater [U.S. Geological Survey, 1980]. The PAs with high groundwater extraction are those located in California, Nebraska, and Texas. Table 9 contains the groundwater, the surface water, and the percentages of each by PA for 1980.

Table 9. Irrigation water sources by producing area, 1980

Producing area	1000 acre-feet/year			Percent of total	
	Ground	Surface	Total	Ground	Surface
1	0.0	6.0	6.0	0.000000	1.000000
2	0.1	4.8	4.9	0.020408	0.979592
3	4.7	15.3	20.0	0.235000	0.765001
4	0.7	8.3	9.0	0.077778	0.922222
5	3.1	18.2	21.3	0.145540	0.854460
6	0.2	1.2	1.4	0.142857	0.857143
7	1.2	8.6	9.8	0.122449	0.877551
8	25.9	3.0	28.9	0.896194	0.103806
9	50.5	41.5	92.0	0.548913	0.451087
10	7.9	88.2	96.1	0.082206	0.917794
11	21.7	14.2	35.9	0.604457	0.395543
12	0.9	16.7	17.6	0.051136	0.948864
13	34.8	98.8	133.6	0.260479	0.739521
14	26.8	50.0	76.8	0.348958	0.651042
15	104.1	80.9	185.0	0.562703	0.437297
16	982.2	344.6	1,326.8	0.740277	0.259723
17	784.8	1,271.2	2,056.0	0.381712	0.618288
18	308.9	134.8	443.7	0.696191	0.303809
19	15.9	24.9	40.8	0.389706	0.610294
20	2.8	1.4	4.2	0.666667	0.333333
21	1.0	0.0	1.0	1.000000	0.000000
22	0.3	0.8	1.1	0.272727	0.727273
23	20.5	2.0	22.5	0.911111	0.088889
24	5.4	0.0	5.4	1.000000	0.000000
25	157.5	126.9	284.4	0.553798	0.446203
26	3.5	7.9	11.4	0.307017	0.692982
27	12.0	16.5	28.5	0.421053	0.578947
28	4.0	5.4	9.4	0.425532	0.574468
29	1.6	11.3	12.9	0.124031	0.875969
30	2.0	22.8	24.8	0.080645	0.919355
31	1.5	9.3	10.8	0.138889	0.861111
32	6.9	7.4	14.3	0.482517	0.517483
33	0.0	1.2	1.2	0.000000	1.000000
34	3.8	7.8	11.6	0.327586	0.672414
35	81.6	15.8	97.4	0.837782	0.162218
36	3.4	1.2	4.6	0.739130	0.260870
37	2.2	3.9	6.1	0.360656	0.639344
38	0.7	0.7	1.4	0.500000	0.500000
39	131.6	13.7	145.3	0.905712	0.094288
40	15.8	0.3	16.1	0.981367	0.018634
41	91.8	9.0	100.8	0.910714	0.089286
42	146.5	5.5	152.0	0.963816	0.036184
43	4.1	3.8	7.9	0.518987	0.481013
44	2,922.0	1,526.4	4,448.4	0.656866	0.343135

Table 9. Continued

Producing area	1000 acre-feet/year			Percent of total	
	Ground	Surface	Total	Ground	Surface
45	1,635.5	444.6	2,080.1	0.786260	0.213740
46	869.7	1,274.5	2,144.2	0.405606	0.594394
47	51.6	20.5	72.1	0.715673	0.284327
48	13.2	1,309.1	1,322.3	0.009983	0.990017
49	41.1	1,068.0	4,109.1	0.010002	0.989998
50	6.3	618.9	625.2	0.010077	0.989923
51	76.4	5,236.7	5,313.1	0.014380	0.985621
52	125.8	823.9	949.7	0.132463	0.867537
53	195.6	20.5	216.1	0.905136	0.094863
54	2,049.1	6,101.0	8,150.1	0.251420	0.748580
55	3,143.9	1,185.0	4,328.9	0.726259	0.273742
56	718.4	44.8	763.2	0.941300	0.058700
57	119.1	13.3	132.4	0.899547	0.100453
58	3,495.9	487.5	3,983.4	0.877617	0.122383
59	1,843.6	75.9	1,919.5	0.960458	0.039542
60	7.8	16.6	24.4	0.319672	0.680328
61	472.9	48.0	520.9	0.907852	0.092148
62	311.6	1,862.5	2,174.1	0.143324	0.856676
63	4,579.2	214.5	4,793.7	0.955254	0.044746
64	109.4	68.0	177.4	0.616685	0.383315
65	2,068.0	372.1	2,440.1	0.847506	0.152494
66	402.5	13.9	416.4	0.966619	0.033381
67	1,007.7	20.6	1,028.3	0.979967	0.020033
68	413.8	119.4	533.2	0.776069	0.223931
69	36.9	39.5	76.4	0.482984	0.517016
70	7.1	12.8	19.9	0.356784	0.643216
71	92.1	215.3	307.4	0.299610	0.700391
72	2,402.1	168.1	2,570.2	0.934597	0.065403
73	144.1	51.6	195.7	0.736331	0.263669
74	709.6	20.8	730.4	0.971523	0.028478
75	200.6	247.7	448.3	0.447468	0.552532
76	763.4	1,145.6	1,909.0	0.399895	0.600105
77	471.6	1,230.2	1,701.8	0.277118	0.722882
78	640.6	1,228.7	1,869.3	0.342695	0.657305
79	223.4	113.4	336.8	0.663302	0.336698
80	460.7	298.2	758.9	0.607063	0.392937
81	10.4	131.4	141.8	0.073343	0.926657
82	53.4	3,011.8	3,065.2	0.017421	0.982579
83	27.3	4,197.2	4,224.5	0.006462	0.993538
84	18.7	1,332.3	1,351.0	0.013842	0.986158
85	39.0	70.3	109.3	0.356816	0.643184
86	355.5	1,496.8	1,852.3	0.191923	0.808077
87	3,940.7	2,412.3	6,353.0	0.620290	0.379711
88	239.1	2,067.4	2,306.5	0.103664	0.896336
89	369.9	560.5	930.4	0.397571	0.602429

Table 9. Continued

Producing area	1000 acre-feet/year			Percent of total	
	Ground	Surface	Total	Ground	Surface
90	462.8	1,677.9	2,140.7	0.216191	0.783809
91	47.5	1,135.6	1,183.1	0.040149	0.959851
92	291.1	4,665.9	4,957.0	0.058725	0.941275
93	1,063.5	10,221.5	11,285.0	0.094240	0.905760
94	4,697.8	13,533.5	18,231.3	0.257678	0.742322
95	77.8	1,486.6	1,564.4	0.049732	0.950269
96	147.9	569.5	717.4	0.206161	0.793839
97	50.4	618.8	669.2	0.075314	0.924686
98	44.8	493.2	538.0	0.083271	0.916729
99	171.4	1,564.8	1,736.2	0.098721	0.901279
100	4,806.5	4,899.6	9,706.1	0.495204	0.504796
101	16,884.6	16,981.6	33,866.2	0.498568	0.501432
102	310.5	42.4	352.9	0.879853	0.120147
103	1312.6	152.6	1,465.2	0.895850	0.104150
104	995.4	4,374.8	5,370.2	0.185356	0.814644
105	364.3	137.3	501.6	0.726276	0.273724

Source: U.S. Geological Survey, 1980.

Efficiencies

The energy requirement for pumping irrigation water will be several times greater than the potential energy of the pumped water. The act of pumping requires more energy because of energy losses in the pump itself, energy losses from internal combustion engines and electric engines, and energy losses in generating electricity. The electric generation efficiencies with respect to the use of fossil fuel are reported in Table 10. The low efficiencies are characteristic of regions where the majority of the electricity generated is from coal, oil, and gas. The high efficiencies characterize regions where hydro and nuclear power are significant sources of the electricity generated.

Table 10. Distribution of energy sources for irrigation and energy efficiencies, 1981

Producing area	Diesel	Gasoline	LP Gas	Natural gas	Electricity	Electric generator efficiency	Overall energy efficiency
1	0.2000	0.8000	0.0000	0.0000	0.0000	0.5110	0.2495
2	0.1344	0.8437	0.0000	0.0000	0.0219	0.5110	0.2498
3	0.0620	0.4806	0.0085	0.0000	0.4490	0.5110	0.3365
4	0.0200	0.5300	0.0100	0.0000	0.4400	0.5110	0.3318
5	0.0213	0.5463	0.0096	0.0000	0.4228	0.5110	0.3282
6	0.1277	0.8011	0.0000	0.0000	0.0712	0.5143	0.2601
7	0.3790	0.4813	0.0000	0.0000	0.1397	0.5250	0.2931
8	0.3800	0.4800	0.0000	0.0000	0.1400	0.5250	0.2932
9	0.4601	0.4214	0.0019	0.0000	0.1170	0.4970	0.2906
10	0.3969	0.5643	0.0000	0.0000	0.0472	0.4204	0.2710
11	0.5576	0.3555	0.0450	0.0000	0.0392	0.4010	0.2779
12	0.4054	0.5168	0.0373	0.0000	0.0371	0.4010	0.2672
13	0.5918	0.3682	0.0100	0.0000	0.0278	0.4228	0.2791
14	0.6294	0.1411	0.0100	0.0000	0.2195	0.4290	0.3095
15	0.6939	0.0680	0.0288	0.0000	0.2093	0.4290	0.3126
16	0.6541	0.0976	0.0943	0.0000	0.1541	0.4290	0.3029
17	0.6500	0.1000	0.1000	0.0000	0.1500	0.4290	0.3021
18	0.7020	0.0710	0.0352	0.0000	0.1919	0.4290	0.3107
19	0.7860	0.0592	0.0570	0.0000	0.0978	0.4290	0.3032
20	0.8095	0.0474	0.0487	0.0013	0.0931	0.4290	0.3040
21	0.6600	0.0100	0.0300	0.0200	0.2800	0.4290	0.3195
22	0.3557	0.0845	0.0163	0.0041	0.5394	0.3780	0.3122
23	0.3126	0.0840	0.0200	0.0097	0.5737	0.3780	0.3125
24	0.3203	0.0797	0.0849	0.0189	0.4961	0.3780	0.3059
25	0.3776	0.2036	0.0424	0.0030	0.3734	0.3780	0.2980
26	0.4000	0.2200	0.0200	0.0000	0.3600	0.3780	0.2980
27	0.3615	0.2414	0.0521	0.0008	0.3443	0.3505	0.2859
28	0.3523	0.4218	0.0364	0.0000	0.1902	0.4314	0.2877
29	0.3800	0.4800	0.0000	0.0000	0.1400	0.5250	0.2932
30	0.3771	0.5925	0.0000	0.0000	0.0394	0.4010	0.2681

Table 10. Continued

Producing area	Diesel	Gasoline	LP Gas	Natural gas	Electricity	Electric generator efficiency	Overall energy efficiency
31	0.3155	0.4321	0.0591	0.0007	0.1958	0.3456	0.2720
32	0.2977	0.2914	0.1032	0.0009	0.3068	0.2969	0.2650
33	0.4110	0.5433	0.0093	0.0000	0.0295	0.4076	0.2657
34	0.1711	0.6794	0.0106	0.0026	0.1362	0.4237	0.2662
35	0.3076	0.0869	0.1325	0.0229	0.4500	0.3780	0.3009
36	0.3428	0.4030	0.0386	0.0386	0.1771	0.4290	0.2831
37	0.4860	0.3071	0.0355	0.0313	0.1397	0.4279	0.2874
38	0.7481	0.0931	0.0499	0.0085	0.1004	0.4290	0.3006
39	0.3706	0.0131	0.0112	0.0004	0.6046	0.3771	0.3191
40	0.3124	0.0776	0.0197	0.0097	0.5807	0.3780	0.3132
41	0.3819	0.0487	0.0465	0.0158	0.5071	0.3639	0.3045
42	0.4346	0.0518	0.1283	0.0225	0.3627	0.3643	0.2966
43	0.4500	0.0775	0.2775	0.0096	0.1854	0.3366	0.2803
44	0.1382	0.2341	0.3981	0.0446	0.1850	0.2959	0.2528
45	0.4755	0.1113	0.1711	0.0312	0.2109	0.3551	0.2849
46	0.8000	0.0800	0.0500	0.0200	0.0500	0.2930	0.2905
47	0.2520	0.0053	0.0100	0.0000	0.7327	0.3619	0.3137
48	0.0100	0.0200	0.0100	0.0000	0.8600	0.3440	0.2709
49	0.0100	0.0200	0.0100	0.0000	0.8600	0.3440	0.2709
50	0.0100	0.0200	0.0100	0.0000	0.8600	0.3440	0.2709
51	0.0571	0.0148	0.0100	0.0419	0.8286	0.3440	0.2827
52	0.1212	0.0144	0.0282	0.0083	0.8218	0.3440	0.2979
53	0.2021	0.0155	0.0773	0.0735	0.6315	0.3340	0.2843
54	0.1088	0.0100	0.0876	0.1082	0.6855	0.3392	0.2832
55	0.3000	0.0100	0.1500	0.2100	0.3300	0.3170	0.2638
56	0.3000	0.0100	0.1500	0.2100	0.3300	0.3170	0.2638
57	0.3338	0.0361	0.1409	0.0946	0.3946	0.3170	0.2734
58	0.1832	0.0069	0.1141	0.2928	0.4029	0.3246	0.2581
59	0.2952	0.0097	0.1475	0.2220	0.3256	0.3170	0.2628
60	0.4058	0.0853	0.3429	0.0869	0.0791	0.3170	0.2672

Table 10. Continued

Producing area	Diesel	Gasoline	LP Gas	Natural gas	Electricity	Electric generator efficiency	Overall energy efficiency
61	0.2377	0.1910	0.3961	0.0303	0.1449	0.3024	0.2599
62	0.0500	0.0100	0.1100	0.0900	0.7400	0.3440	0.2867
63	0.1456	0.0007	0.0730	0.5722	0.2085	0.3175	0.2329
64	0.1806	0.1225	0.2844	0.2509	0.1615	0.3030	0.2465
65	0.0686	0.0053	0.0504	0.5520	0.3123	0.2930	0.2234
66	0.0770	0.0113	0.1050	0.5557	0.2423	0.2930	0.2236
67	0.0600	0.0000	0.0200	0.5500	0.3500	0.2930	0.2214
68	0.0748	0.0099	0.0939	0.5549	0.2563	0.2930	0.2233
69	0.1657	0.1074	0.2122	0.3108	0.1999	0.2930	0.2407
70	0.0636	0.0004	0.0201	0.5474	0.3485	0.2930	0.2217
71	0.0600	0.0000	0.0200	0.5500	0.3500	0.2930	0.2214
72	0.0632	0.0016	0.0208	0.5500	0.3500	0.2930	0.2229
73	0.0600	0.0000	0.0200	0.5500	0.3500	0.2930	0.2214
74	0.0632	0.0016	0.0208	0.5500	0.3500	0.2930	0.2229
75	0.0600	0.0000	0.0200	0.5500	0.3500	0.2930	0.2214
76	0.0600	0.0000	0.0200	0.5500	0.3500	0.2930	0.2214
77	0.0500	0.0100	0.1100	0.0900	0.7400	0.3440	0.2867
78	0.0906	0.0153	0.0277	0.5500	0.3500	0.2930	0.2362
79	0.0600	0.0000	0.0200	0.5500	0.3500	0.2930	0.2214
80	0.1000	0.0200	0.0300	0.5500	0.3500	0.2930	0.2407
81	0.0600	0.0000	0.0200	0.5500	0.3500	0.2930	0.2214
82	0.0740	0.0069	0.0211	0.0563	0.8417	0.3440	0.2955
83	0.0499	0.0099	0.1090	0.0892	0.7420	0.3440	0.2869
84	0.0572	0.0094	0.0672	0.1563	0.7195	0.3342	0.2788
85	0.0151	0.0011	0.0017	0.2104	0.7745	0.2930	0.2465
86	0.0249	0.0007	0.0007	0.1685	0.8051	0.3040	0.2566
87	0.0136	0.0008	0.0012	0.2046	0.7818	0.2930	0.2466
88	0.0333	0.0022	0.0000	0.0000	0.9645	1.1073	0.9517
89	0.0400	0.0000	0.0000	0.0000	0.9600	0.3440	0.3031
90	0.2000	0.0100	0.0100	0.0000	0.7800	0.4170	0.3521

Table 10. Continued

Producing area	Diesel	Gasoline	LP Gas	Natural gas	Electricity	Electric generator efficiency	Overall energy efficiency
91	0.2000	0.0100	0.0100	0.0000	0.7800	0.4170	0.3521
92	0.0096	0.0184	0.0088	0.0000	0.8753	0.7581	0.5942
93	0.0000	0.0000	0.0000	0.0000	1.0000	3.7600	3.3133
94	0.0096	0.0090	0.0001	0.0006	0.9808	3.7350	3.2333
95	0.0058	0.0058	0.0000	0.0000	0.9884	3.7600	3.2780
96	0.0000	0.0000	0.0000	0.0000	1.0000	3.7600	3.3133
97	0.0000	0.0000	0.0000	0.0000	1.0000	3.7600	3.3133
98	0.0000	0.0000	0.0000	0.0000	1.0000	3.7600	3.3133
99	0.0363	0.0000	0.0000	0.0091	0.9546	2.2416	1.8984
100	0.0800	0.0000	0.0000	0.0200	0.9000	0.4170	0.3589
101	0.0800	0.0000	0.0000	0.0200	0.9000	0.4170	0.3589
102	0.0800	0.0000	0.0000	0.0200	0.9000	0.4170	0.3589
103	0.0800	0.0000	0.0000	0.0200	0.9000	0.4170	0.3589
104	0.0800	0.0000	0.0000	0.0200	0.9000	0.4170	0.3589
105	0.0800	0.0000	0.0000	0.0200	0.9000	0.4170	0.3589

The mechanical efficiency of the internal combustion and electric engines used in irrigation are in Table 11. The horsepower-hours (hp-hr) per unit of energy is the actual usable energy the engine produces to drive the pump. Mechanical efficiency is defined as the usable energy produced divided by the potential energy in a unit of the energy source.

Table 11. Mechanical efficiencies of common motors used for irrigation

Energy source	HP-HR/unit energy[1]	Energy units	Mechanical efficiency
Diesel fuel	16.66	gallon	0.3030
Gasoline	11.50	gallon	0.2361
LP gas	9.20	gallon	0.2479
Natural gas	82.2	1000 ft^3 (mcf)	0.1961
Electricity	1.18	Kwh	0.8812

Source: Gilley and Watts, 1977.

[1]One HP-HR is equivalent to 641.616 Kcal.

The efficiency of a new or well maintained pump is about 75 percent. The efficiency level will be lower than this if the pump is not maintained. The pump drive method can also result in a lower efficiency. Gearboxes to change the drive direction or belts will reduce the efficiency. The efficiency of the pump will be reduced 3 percent with the use of a gearbox, 5 percent with the use of V-belts, and 20 percent with the use of flat belts. These additional drive losses are associated with internal combustion engines because the engine can not be set on its side to provide a direct drive to the pump.

The mechanical efficiency of the motor and pump previously outlined are attainable performance criteria. The efficiency attained by producers is often less than the performance criteria because of poorly tuned engines and improperly adjusted pumps. Tests done by the University of Nebraska on a sample of pumping units found an average performance rating of 77 percent of the performance criteria [Schroeder and Fischbach, 1983]. The performance rating will depend on how well the pumping unit is maintained. The performance rating might also be dependent on groundwater depth, on the hypothesis that pumping units are better maintained when pumping costs are high.

The overall energy efficiency in a PA will depend on the mechanical efficiency of the energy source (see Table 10), the percent distribution of the energy sources, and the electric energy generation efficiency. The overall efficiency is a weighted average of the efficiency of each energy source. The overall energy efficiency is calculated as:

$$OEE_i = \sum_{j=1}^{4} ME_j * WP_{ij} + ME_5 * WP_{i5} * EE_i \qquad (8)$$

where: OEE_i is the overall energy efficiency in the ith PA,

$j = 1,2,3,4$ for diesel fuel, gasoline, LP gas, and natural gas respectively, the fifth subscript is electricity,

ME_j is the mechanical energy efficiency for the jth power source,

WP_{ij} is the proportion of the jth power source in the ith PA, and

EE_i is the electrical efficiency in the ith PA.

Table 10 contains the distribution of energy sources and the overall efficiency of the ith PA.

The energy required to apply irrigation water depends on the system. Gravity systems do not require the pumping of water. Sprinkler systems require energy to apply water. The amount of energy depends on the sprinkler system. The greater the sprinkler pressure (head), the greater the energy requirement. The head required for the major sprinkler systems are in Table 12. The low pressure center pivot systems are limited in their use by the infiltration rate and slope of the land.

Table 12. Head requirements for sprinkler systems

Sprinkler method	Head (feet)	PSI
Center pivot - high pressure	161.7	70
Center pivot - low pressure	69.3	30
Tow line/ride roll	115.5	50
Hand move	115.5	50
Solid set	115.5	50
Gun	207.9	90
Gated pipe	11.55	5

The energy use for applying water will depend on the distribution of the application methods for a producing area. The proportions of total irrigation by method is in Table 13. There are four sprinkler systems, four gravity, and drip or trickle irrigation.

Table 13. Proportion of irrigation by system

Producing area	Center pivot	Mechanical move	Hand move	Solid set	Gated pipe	Ditch	Flood (values)	Flood (other)	Drip/ trickle
1	0.0	.1209	.3493	.2365	.0083	.0109	.2612	0.0	.0129
2	0.0	.1209	.3493	.2365	.0083	.0109	.2612	0.0	.0129
3	0.0	.1209	.3493	.2365	.0083	.0109	.2612	0.0	.0129
4	0.0	.1209	.3493	.2365	.0083	.0109	.2612	0.0	.0129
5	0.0	.1209	.3493	.2365	.0083	.0109	.2612	0.0	.0129
6	0.0	.1209	.3493	.2365	.0083	.0109	.2612	0.0	.0129
7	.1953	.3585	.3647	.0109	.0069	.0023	.0046	.0568	0.0
8	.1953	.3585	.3647	.0109	.0069	.0023	.0046	.0568	0.0
9	.1953	.3585	.3647	.0109	.0069	.0023	.0046	.0568	0.0
10	.1953	.3585	.3647	.0109	.0069	.0023	.0046	.0568	0.0
11	.1953	.3585	.3647	.0109	.0069	.0023	.0046	.0568	0.0
12	.1953	.3585	.3647	.0109	.0069	.0023	.0046	.0568	0.0
13	.0435	.1926	.7153	.0097	.0073	.0025	.0003	.0278	.0010
14	.1343	.3608	.3260	.0206	.0243	0.0	.0159	.1179	.0001
15	.2979	.4841	.1659	.0157	0.0	.0044	0.0	.0111	.0210
16	.0250	.2619	.0552	.1264	.0201	.1797	.0216	.2447	.0654
17	.0154	.1078	.0485	.1020	.0324	.1952	.0070	.4594	.0324
18	.5391	.3583	.0380	.0157	.0062	.0178	.0087	.0072	.0091
19	.5391	.3583	.0380	.0157	.0062	.0178	.0087	.0072	.0091
20	.5391	.3583	.0380	.0157	.0062	.0178	.0087	.0072	.0091
21	.5391	.3583	.0380	.0157	.0062	.0178	.0087	.0072	.0091
22	.3791	.4017	.1489	.0483	0.0	.0031	0.0	.0189	0.0
23	.3791	.4017	.1489	.0483	0.0	.0031	0.0	.0189	0.0
24	.3791	.4017	.1489	.0483	0.0	.0031	0.0	.0189	0.0
25	.3791	.4017	.1489	.0483	0.0	.0031	0.0	.0189	0.0
26	.3791	.4017	.1489	.0483	0.0	.0031	0.0	.0189	0.0
27	.3791	.4017	.1489	.0483	0.0	.0031	0.0	.0189	0.0
28	.3791	.4017	.1489	.0483	0.0	.0031	0.0	.0189	0.0
29	.3791	.4017	.1489	.0483	0.0	.0031	0.0	.0189	0.0
30	.4481	.2350	.2138	.0550	0.0	.0032	0.0	.0449	0.0

Table 13. Continued

Producing area	Center pivot	Mechanical move	Hand move	Solid set	Gated pipe	Ditch	Flood (values)	Flood (other)	Drip/ trickle
31	.4481	.2350	.2138	.0550	0.0	.0032	0.0	.0449	0.0
32	.4481	.2350	.2138	.0550	0.0	.0032	0.0	.0449	0.0
33	.4481	.2350	.2138	.0550	0.0	.0032	0.0	.0449	0.0
34	.4481	.2350	.2138	.0550	0.0	.0032	0.0	.0449	0.0
35	.4481	.2350	.2138	.0550	0.0	.0032	0.0	.0449	0.0
36	.4481	.2350	.2138	.0550	0.0	.0032	0.0	.0449	0.0
37	.1173	.1581	.3238	.0897	0.0	0.0	0.0	.3112	0.0
38	.1173	.1581	.3238	.0897	0.0	0.0	0.0	.3112	0.0
39	.7055	.1843	.0632	.0166	.0094	.0031	0.0	.0177	.0003
40	.7055	.1843	.0632	.0166	.0094	.0031	0.0	.0177	.0003
41	.7055	.1843	.0632	.0166	.0094	.0031	0.0	.0177	.0003
42	.7055	.1843	.0632	.0166	.0094	.0031	0.0	.0177	.0003
43	.7055	.1843	.0632	.0166	.0094	.0031	0.0	.0177	.0003
44	.0606	.0378	.0021	.0250	.2075	.0462	.1715	.4671	0.0
45	.0319	.0281	.0074	.0204	.1142	.0693	.0924	.6344	.0019
46	.0020	.0012	.0021	.0231	.0496	.0457	.2045	.6717	.0002
47	.6823	.0781	.0194	.0013	0.0	.0204	0.0	.1751	.0233
48	.0404	.0870	.0305	.0008	.0301	.1938	0.0	.6174	0.0
49	.0314	.1506	.0685	.0006	.0178	.0746	.0089	.6001	0.0
50	.0404	.0870	.0305	.0008	.0301	.1938	0.0	.6174	0.0
51	.0547	.0936	.0121	.0003	.0071	.3071	.0071	.4539	0.0
52	.5413	.1774	.0638	.0289	.0396	.0559	.0042	.1704	0.0
53	.5413	.1774	.0638	.0289	.0396	.0559	.0042	.1704	0.0
54	.1969	.0663	.0168	.0076	.0628	.2964	.0054	.3469	.0009
55	.5557	.0647	.0506	.0003	.2130	.1087	0.0	.0070	0.0
56	.5557	.0647	.0506	.0003	.2130	.1087	0.0	.0070	0.0
57	.5295	.1938	.0690	.0037	.1630	.0340	0.0	.0070	0.0
58	.4003	.0655	.0187	.0004	.4335	.0571	.0067	.0177	0.0
59	.4003	.0655	.0187	.0004	.4335	.0571	.0067	.0177	0.0
60	.5295	.1938	.0690	.0037	.1630	.0340	0.0	.0070	0.0
61	.2790	.0500	.0246	.0211	.1883	.0312	.0434	.3605	.0018

Table 13. Continued

Producing area	Center pivot	Mechanical move	Hand move	Solid set	Gated pipe	Ditch	Flood (values)	Flood (other)	Drip/ trickle
62	.0845	.0201	.0227	.0013	.0769	.3743	.0230	.3971	0.0
63	.3386	.0393	.0067	.0022	.4285	.1122	.0384	.0339	.0001
64	.2790	.0500	.0246	.0211	.1883	.0312	.0434	.3605	.0018
65	.2771	.0348	.0084	.0037	.4683	.1218	.0141	.0682	0.0
66	.2771	.0348	.0084	.0037	.4683	.1218	.0141	.0682	0.0
67	.0896	.1831	.0227	.0087	.3898	.1791	.0216	.1050	.0004
68	.0896	.1831	.0227	.0087	.3898	.1791	.0216	.1050	.0004
69	.0739	.2238	.2166	.0015	.0925	.0689	0.0	.2729	.0499
70	.0061	.0110	.0070	.0049	.0972	.0240	.0066	.8430	.0002
71	.0061	.0110	.0070	.0049	.0972	.0240	.0066	.8430	.0002
72	.1052	.0825	.0097	.0053	.3922	.3218	.0432	.0389	.0011
73	.1052	.0825	.0097	.0053	.3922	.3218	.0432	.0389	.0011
74	.4019	.2038	.0752	.0012	.0645	.0724	.0191	.1606	.0013
75	.4019	.2038	.0752	.0012	.0645	.0724	.0191	.1606	.0013
76	.1151	.1400	.0969	.0006	.2296	.2307	.0299	.1550	.0022
77	.2490	.1891	.0374	0.0	.0448	.1633	0.0	.4694	0.0
78	.0283	.0269	.0143	.0827	.1107	.2384	.0224	.4690	.0072
79	.2334	.0644	.0095	.0003	.0771	.4405	.1732	.5543	.0097
80	.2334	.0644	.0095	.0003	.0771	.4405	.1732	.5543	.0097
81	.0566	.0243	.0058	.0017	.2589	.3153	.0840	.2528	.0056
82	.0422	.0571	.0504	.0097	.0155	.0877	.0117	.7294	.0009
83	.0777	.2563	.0161	.0003	.0032	.0688	0.0	.5778	0.0
84	.0016	.0859	.0921	.0009	.0172	.1858	0.0	.6142	.0023
85	.0206	.0958	.0733	.0023	.1286	.1928	.0185	.4625	.0057
86	.0206	.0958	.0733	.0023	.1286	.1928	.0185	.4625	.0057
87	.0585	.0570	.0165	.0032	.1911	.5635	.0111	.0982	.0008
88	.0390	.1725	.1180	.0003	.0319	.1741	.0022	.4527	.0093
89	.0263	.1489	.0537	.0019	.0900	.1082	.0023	.5686	0.0
90	.0419	.0821	.0208	.0109	.0387	.0748	.0181	.7126	0.0
91	.0419	.0821	.0208	.0109	.0387	.0748	.0181	.7126	0.0

Table 13. Continued

Producing area	Center pivot	Mechanical move	Hand move	Solid set	Gated pipe	Ditch	Flood (values)	Flood (other)	Drip/ trickle
92	.1181	.1365	.3481	.0015	.0163	.0319	0.0	.3461	.0015
93	.2109	.2586	.1712	.0490	.0313	.1822	.0203	.0751	.0013
94	.1211	.1486	.1350	.0144	.0393	.2677	.0099	.2640	0.0
95	.0134	.2370	.1969	.0084	.0061	.0239	.0005	.5137	0.0
96	.0116	.1472	.6033	.0564	.0074	.0298	.0023	.1415	.0005
97	0.0	.0867	.8801	.0029	.0009	.0056	.0013	.0217	.0023
98	.1116	.1369	.0094	.0234	.0006	.0188	.0007	.6985	0.0
99	.0241	.2607	.1213	.0448	.0078	.0553	.0231	.4626	.0003
100	.0090	.0792	.0971	.0278	.0727	.1885	.1044	.4153	.0060
101	.0150	.0301	.0866	.0345	.2235	.2758	.1773	.1417	.0155
102	.0386	.0181	.1934	.1470	.1506	.2167	.0268	.1668	.0418
103	.0019	.0692	.6115	.0811	.2037	.0120	.0073	.0040	.0093
104	.0240	.0338	.1611	.0792	.1175	.1559	.0532	.2882	.0871
105	0.0	.1565	.0145	.0115	0.0	.0144	.0658	.7373	0.0

Source: U.S. Bureau of Commerce, 1978.

Energy Requirements

The energy requirements to obtain and apply one acre foot of water can be calculated from the coefficients previously outlined. Energy requirements can be broken down into that required to obtain the water and that required to apply the water. The energy required to obtain on acre-foot of groundwater is calculated by:

$$ERG_i = \frac{GL_i * .88080913}{OEE_i * PE_i * PR_i} \qquad (9)$$

where: ERG_i is the energy (1000 Kcal) to obtain one acre-foot of groundwater in the ith PA, .88080913 is the energy (1000 Kcal) to lift one acre-foot of water one foot,

PR_i is the performance rating of pumping units in the ith PA, and

the remaining variables are as defined in equations 7 and 8.

It will be assumed that the surface water is lifted to the field with electric engines. The energy required to obtain one acre-foot of surface water will be:

$$ERS_i = \frac{SL_i * .88080913}{EE_i * PE_i * PRS} \qquad (10)$$

where: ERS_i is the energy (1000 Kcal) to obtain one acre-foot of surface water in the ith PA,

PRS is the performing rating of surface water pumps, and the remaining variables are as previously defined.

Total energy requirements to obtain and apply one acre-foot of water will be a weighted average of the energy to obtain ground and surface water, plus the energy to apply the water. The total energy requirements are:

$$ER_i = GW_i * ERG_i + SW_i * ERS_i + ERA_i \qquad (11)$$

where the variables are as previously defined.

Table 14 contains the energy required to obtain and apply one acre-foot of water and the total energy to obtain and apply one acre-foot of water. The energy requirements are obtained from the data reported in this report.

Table 14. Energy requirements for irrigation

Producing area	Ground (1000 Kcal)	Surface (1000 Kcal)	Apply (1000 Kcal)	Total (1000 Kcal)
1	482.5	0.0	732.3	732.3
2	481.9	0.0	731.4	741.2
3	357.7	0.0	543.0	627.0
4	362.8	0.0	550.6	578.9
5	366.8	0.0	556.7	610.1
6	462.8	0.0	702.4	768.6
7	355.6	0.0	831.5	875.1
8	355.5	0.0	831.2	1,149.8
9	358.7	0.0	838.7	1,035.5
10	384.6	0.0	899.3	930.9
11	375.1	0.0	877.0	1,103.7
12	390.1	0.0	912.1	932.1
13	284.0	25.0	882.5	975.0
14	431.6	24.6	709.0	875.7
15	746.7	24.6	831.1	1,262.0
16	475.0	24.6	435.8	793.8
17	228.4	24.6	252.0	354.4
18	222.1	24.6	844.5	1,006.6
19	227.6	24.6	865.4	969.1
20	227.0	24.6	863.1	1,022.6

Table 14. Continued

Producing area	Ground (1000 Kcal)	Surface (1000 Kcal)	Apply (1000 Kcal)	Total (1000 Kcal)
21	216.0	24.6	821.2	1,037.2
22	348.0	0.0	840.8	935.7
23	347.6	0.0	840.0	1,156.7
24	355.1	0.0	858.1	1,213.3
25	364.5	0.0	880.9	1,082.8
26	364.5	0.0	880.9	992.8
27	380.0	0.0	918.2	1,078.1
28	377.6	0.0	912.4	1,073.1
29	370.5	0.0	895.3	941.2
30	427.1	0.0	961.3	995.8
31	421.0	0.0	947.5	1,006.0
32	432.1	0.0	972.6	1,181.1
33	431.0	0.0	970.0	970.0
34	430.1	0.0	968.2	1,109.1
35	380.5	0.0	856.5	1,175.3
36	404.5	0.0	910.4	1,209.3
37	429.1	0.0	625.1	779.8
38	410.2	0.0	597.6	802.7
39	331.2	0.0	848.3	1,148.3
40	337.5	0.0	864.3	1,195.5
41	347.1	0.0	889.0	1,205.1
42	356.4	0.0	912.7	1,256.2
43	377.1	0.0	965.8	1,161.5
44	516.8	47.6	134.9	490.7
45	427.7	36.4	83.7	427.7
46	631.7	82.6	25.4	330.7
47	355.7	123.3	719.1	1,008.7
48	1,090.3	123.2	154.8	287.7
49	802.0	211.0	241.0	457.9
50	1,022.6	116.1	154.8	280.0
51	93.5	234.5	151.9	384.4
52	803.2	307.6	755.1	1,128.4
53	175.6	140.6	791.2	963.5
54	502.8	108.4	282.7	490.2
55	765.2	200.1	718.1	1,328.6
56	229.8	200.1	718.1	946.2
57	362.4	55.6	806.9	1,138.5
58	891.8	112.2	530.3	1,326.7
59	755.2	114.8	520.8	1,250.7
60	497.2	55.6	825.7	1,022.4
61	463.2	248.6	404.4	847.8
62	373.8	211.7	124.1	359.0

Table 14. Continued

Producing area	Ground (1000 Kcal)	Surface (1000 Kcal)	Apply (1000 Kcal)	Total (1000 Kcal)
63	1,046.3	251.5	471.5	1,482.2
64	488.3	263.6	426.3	828.5
65	2,759.9	136.3	410.7	2,770.5
66	1,273.7	136.3	410.4	1,646.1
67	1,625.8	272.6	365.3	1,964.1
68	938.1	272.6	362.2	1,151.3
69	872.1	272.6	592.3	1,154.5
70	1,311.7	149.9	34.5	598.9
71	1,962.0	149.9	34.6	727.4
72	1,850.7	428.9	248.9	2,006.5
73	1,147.1	428.9	250.6	1,208.3
74	1,365.3	200.4	841.7	2,173.8
75	853.4	200.4	847.4	1,340.0
76	1,704.1	132.3	425.6	1,186.4
77	430.1	252.6	452.5	754.3
78	1,000.6	116.2	174.2	593.5
79	1,694.1	60.1	396.7	1,540.7
80	1,052.1	116.2	364.9	1,049.2
81	1,299.6	396.8	114.6	577.7
82	253.4	177.5	143.0	321.8
83	465.6	670.8	321.9	991.5
84	405.4	159.9	166.9	330.2
85	981.5	865.8	205.7	1,112.8
86	1,013.2	256.1	197.6	599.0
87	1,684.7	366.8	148.5	1,332.8
88	259.1	146.4	91.6	249.6
89	673.2	522.3	197.8	780.1
90	460.7	45.1	117.1	252.0
91	723.4	45.1	117.1	189.4
92	375.5	216.9	266.1	492.3
93	66.5	70.6	55.4	125.6
94	101.7	69.6	34.3	112.2
95	66.3	28.4	35.7	66.0
96	37.7	41.9	63.1	104.1
97	63.4	85.6	74.5	158.4
98	42.1	25.0	22.8	49.3
99	71.1	26.7	61.2	92.4
100	499.0	117.4	155.3	461.7
101	695.4	325.3	126.8	636.6
102	617.6	574.5	305.6	918.1
103	589.0	1,188.5	546.2	1,197.6
104	859.0	1,394.1	255.1	1,550.0
105	576.7	729.4	130.5	749.0

VIII. COSTS

The irrigation cost components for the model, the C_{ij}'s in Figure 1, include the application cost by system, the cost of acquiring ground- and surface water, and the cost of converting land to irrigation. The application costs are a function of the system (capital costs and pressure requirements), the source of energy (diesel, LP gas, natural gas, and electricity), the quantity of water applied, and a number of input parameters.

The cost of irrigating with groundwater for the various systems can be calculated in the following form:

$$C_{ij} = f(WD_j, PSI_i, ENER_j, SYST_i) \qquad (12)$$

where: C_{ij} is the cost per applied unit of water for system i in PA_j,

WD_j is the water pumping depth in PA_j,

PSI_i is the pressure requirement for system i,

$ENER_j$ is the energy source mix in PA_j, and

$SYST_i$ are other characteristics of the system such as the capital cost, labor costs, and repair costs.

The data required to calculate the costs are in Section VI and system specific data will be obtained from the Oklahoma State University irrigation cost program.

The cost of irrigating with surface water will include the cost of applying water plus the cost of the water delivered to the farm. The application costs are calculated the same as for groundwater, except total head requirements are less because the water is being pumped from the surface. The cost of water delivered to the farm is the amount the irrigation organization charges the user of the water. Surface water costs were obtained from Bureau of Reclamation projects [U.S. Bureau of Reclamation, Annual Report] and the 1978 Census of Irrigation Organizations. The surface water costs for these two sources for California are in Table 15. The number of Bureau of Reclamation projects in

Table 15. Surface water costs

Producing area	Bureau of Reclamation ($/ac)	Census ($/ac)	Census ($/ac-ft)
99	9.03	6.69	2.52
100	N.A.	13.81	3.39
101	N.A.	58.36	10.47
102	15.97	12.02	6.35
103	20.29	57.54	31.48
104	.88	59.18	17.25
105	N.A.	25.19	4.92

these producing areas are limited and charges are not reported for all projects. The water cost for Bureau projects are generally less than other projects because other agencies must recover the full cost of the irrigation project. The Census of Irrigation Organizations data on surface water costs is a truer representation of water costs.

The cost of converting dryland to irrigated land will be minimal. It will be assumed that all new irrigation development will utilize center pivots. The irrigation cost component will include the cost of the system, depreciation, well costs, etc. As a result, there are few costs left that could be allocated to conversion of the land.