The CARD/RCA WATER SECTOR MODEL

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Introduction

Water has become a major input into agriculture production in the United States. Irrigation in the Western United States has been important in crop production and will continue to be important. Irrigation is also becoming more important in areas of the southeast. The use and conservation of water, as well as the importance of irrigation in the conservation of soil, are areas of concern as outlined in the 1977 Soil and Water Resources Conservation Act. Therefore, it is necessary for the CARD/RCA programming models to incorporate a water sector.

Model Specification

Water has many uses in agriculture and the economy as a whole. In terms of the CARD/RCA model the uses can be viewed as endogenous and exogenous crop and livestock uses, and nonagricultural uses such as industrial, residential, and fish and wildlife. The sources of water can be surface water and groundwater, recognizing that in many areas there is an interchange between ground and surface sources that makes such a distinction inappropriate. Figure 1 is a diagram of the major factors that influence the use of water in agriculture.

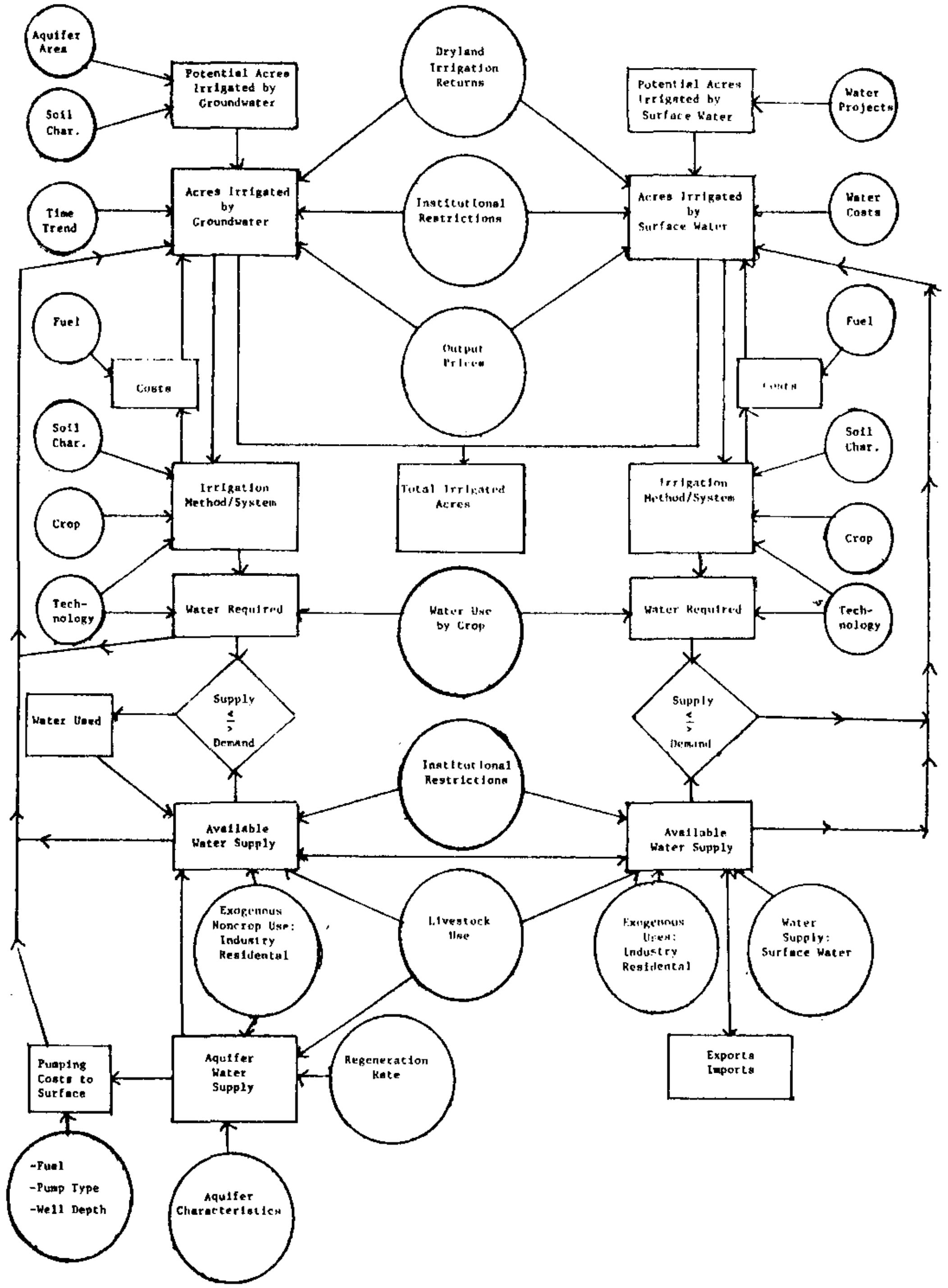

Figure 1. A water model.

Modelling the CARD/RCA85 water sector involves incorporating the relationships illustrated in Figure 1 into a linear programming framework. A schematic of the model is presented in Figure 2. The schematic is for two producing areas (PA's), i and j, with the remaining producing areas being of similar form along the block diagonal specification. The specification collapses down all land classes and rotations so the variables should be viewed as vectors rather than a single variable.

The model specification will allow two approaches to analyze water use. The first and more general model is a flow model. Surface water is allowed to flow to the area and crop of its highest value use in agriculture. This would involve possibilities such as allowing the water to flow downstream for use, or using nearly all of the water upstream and leaving little for downstream use, or diverting water from one river basin to another, or a pattern of use similar to that which now exists.

The second approach, to be referred to as the restricted model, would restrict surface water use to the present pattern to take account of water rights. Most of the surface water rights have been appropriated in the Western United States and producers will continue to use water as they have in the past. The model in Figure 2 is modified by specifying the surface water available for the producing area, allowing only present or negotiated exports and imports of water, and not allowing outflows from one producing area to complement water supply in the downstream producing areas.

The model separates groundwater from surface water because of the different costs, characteristics, and rights associated with each. There are some areas where groundwater and surface water are indistinguishable because of the active interchange of water from one source with the other. The primary areas where this occurs are riverbed deposits. The majority of groundwater sources have very little or slow water interchange with surface water which requires the two sources to be handled separately.

Restraints \ Activities			IRROTGW(i)	APPLYGW(i)	DEPLGW(i)	IRROTSW(i)	APPLYSW(i)	EXPORTSW(i)	IMPORTSW(i)	OUTFLOWS(i)	CNSWD-I(i)	CNGWD-I(i)	IRROTGW(j)	APPLYGW(j)	DEPLGW(j)	IRROTSW(j)	APPLYSW(j)	EXPORTSW(j)	IMPORTSW(j)	OUTFLOWS(j)	CNSWD-I(j)	CNGWD-I(j)	
Objective Function			C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	
		PA_1																					
Gr. Water Required(i)			A	-B																			
Gr. Water Dependable(i)				1	-1																		
Gr. Water Depletable(i)					1																		
Gr. Water Acres(i)			K									-F											
S. Water Required(i)						A	-B																
S. Water Supply(i)							1	1	-M	1								-M	1	-1			
S. Water Acres(i)						N					-E												
Dryland Acres(i)											D	D											
Gr. Water Required(j)													A	-B									
Gr. Water Dependable(j)														1	-1								
Gr. Water Depletable(j)															1								
Gr. Water Acres(j)													K									-F	
S. Water Required(j)																A	-B						
S. Water Supply(j)								-M	1	-1							1	1	-M	1			
S. Water Acres(j)																N					-E		
Dryland Acres(j)																					D	D	
																						....	PA_{105}

Figure 2. A schematic of the water sector for two producing areas.

Model definitions

Activities

IRROTGW (k) is a vector of irrigated rotations using groundwater over all land groups, tillage practices, and conservation practices,

APPLYGW (k) is the application of groundwater using a composite system,

DEPLGW (k) is an activity that uses depletable groundwater and therefore allows cost adjustments as water depth drops over time, water depth changes over the season could be handled by depletion activities for differing depths,

IRROTSW (k) is a vector of rotations using surface water for irrigation across all land groups, tillages, and conservation practices,

APPLYSW (k) is the application of surface water using a composite system,

EXPORTS (k) is the transfer of water, exclusive of natural flows, from producing area k to producing area j, $k \neq j$,

is the water received, exclusive of natural flows, in producing area k from producing area i, $k \neq i$,

OUTFLOWS(k) is the stream flow from producing area k that will flow downstream for use in producing area n, $k \neq n$,

CNSWD-I (k) the conversion of dryland acres to irrigated acres using surface water, CNGWD-I (k) is the conversion of dryland acres to irrigated acres using groundwater, and

k is the producing areas where irrigation is modelled.

Constraints

Gr. Water required (k) is an accounting row of groundwater,

Gr. Water Dependable (k) is the supply of groundwater for endogenous crops that is recharged at a rate equal to withdrawals such that pumping depth is constant over time,

Gr. Water Depletable (k) is the groundwater supply that is drawn down over time because withdrawals exceed recharge,

Gr. Water Acres (k) is a vector of the maximum acres irrigable with groundwater due to the formation and location of groundwater, across land groups,

S. Water Required (k) is an accounting row for surface water,

S. Water Supply (k) is the surface water available for endogenous agricultural uses,

S. Water Acres (k) is the supply of surface water available for endogenous agricultural uses,

Dryland Acres (k) is a vector of maximum dryland acres that can be converted to irrigation, across land groups, and k is a subscript for producing area across land groups.

Elements

C is the cost associated with each activity,

A is a vector of crop water use coefficients,

B is an element that takes into account water losses that occur between withdrawal and application,

K is a matrix of land group acres used for each acre irrigated, by groundwater,

F is a vector of land brought into groundwater irrigation, by land group,

N is a matrix of land group acres used for each acre irrigated by surface water,

E is a vector of land brought into surface water irrigation, by land group,

D is a vector of dryland acres converting to irrigation by land group, and

M is the net quantity of water received from importing water from another producing area.

Constraint characteristics

Groundwater

To limit groundwater use to its realistic potential, not only are limits on water quantities need be known but also the associated land area irrigatable and how this area changes as water is depleted. The cost of pumping water increases with water depletion so depth to water changes need to be known to update pumping cost changes.

Dependable groundwater supply is water available for use without depleting the volume stored. Annual recharge to an aquifer minus any nonagricultural and exogenous agricultural withdrawals from that aquifer estimates the dependable groundwater available for irrigation.

Depletable groundwater available to irrigation lies in storage. Not all groundwater stored in a region may be of sufficient quality to classify it as available for irrigation. Some aquifers are too saline for irrigation. Others have water which is too bound or has too shallow of a saturated thickness to allow it to be pumped at a sufficient rate for irrigation. To include groundwater which has yields too low for irrigation would grossly overstate water availability. Therefore, depletable groundwater available for irrigation should include only those volumes of water with the proper characteristics.

Acreage restrictions will prevent land from coming into production for which production is not physically possible. Land area over the aquifer minus unsuitable acreage will determine this acreage constraint.

As groundwater is mined, the acres irrigable will decline. The acreage restrictions will need to be corrected for this. To do this we must obtain the relationship between mining, watertable decline, and the reduced acreage.

Since pumping costs increase with watertable declines, the aforementioned relationship (between mining water and watertable decline) along with the deeper pumping depth's affect on costs should give an estimate for increased pumping cost.

Surface Water

Limits on irrigation with surface water can be established under two different assumptions on the future use of water. Under the restricted model specification, now established water rights will remain in effect so that future irrigation will be equivalent to the level found today plus future public irrigation projects. The general model relaxes the institutional constraint of prior established water rights limiting water use by its physical limitations. Policy analysis can be made under either or both scenarios, depending on the user's choice. Limiting maximum surface irrigation to past levels will require knowledge of what those limits are. Since the mix of crops produced in a PA can change, water use could increase with no change in acres irrigated (and visa versa). Therefore both acres irrigable and water available will need to be limited to model surface water irrigation under the restricted model.

Under the general model, water can move to down stream producing area's or be used in upstream producing areas according to its highest value in use. The flow aspect of water becomes important here along with considerations of water transfers, treaties, compacts, exogenous uses, and instream flow requirements. In many areas water may be available but suitable land may not be so, again, restrictions on acreages must also be determined. The surface water available to irrigation will be that quantity of water available after all other water demands are met. Supply effects of water transfers must also be accounted for. By adjusting streamflow for water transfers and subtracting offstream (non-agricultural and exogenous agricultural) and instream (of which fish and wildlife is usually greatest) demands, surface water, right-hand-side quantities will be determined.

Land Conversion

The conversion of dryland acres to irrigated acres is constrained by the quantity of dryland acres. The conversion rate in the model will be bounded to prevent an instantaneous conversion of dryland acres to irrigated acres. The bounds will be based on past rates of conversion of dryland to irrigated land in the producing area. Land conversion will require composite acres of the land groups, as opposed to the a conversion activity for each land group.

Element characteristics

The water requirement, vector A, will include the water applied for crop consumptive use plus the water lost during the application process. Water losses include evaporation and runoff that occurs during application. Application efficiency changes over time would be incorporated into the vector A. Water losses that occur during conveying the water from the source to the field are accounted for in the element B. The losses for groundwater will differ from surface water, surface water losses are higher. The value of B will be less than or equal to one, which indicates for each unit of water extracted from the source, less than one unit arrives at the field. Conveyance efficency gains over time would be reflected in B. Conveyance losses will also occur in the exportation and importation of water. The element M ($\leq$ 1) is designed to reflect the water loss that occurs in transfering water from one producing are to another. The value of M will differ for each transfer.

The quantity of acres required to irrigate one acre may depend on the land class as well as the irrigation system. There is a one to one correspondence in the majority of instances. The center pivot corners that are not irrigated, the need for canals, and portions of land non-irrigable, would result in more than one potentially irrigable acre required to irrigate one acre.

The conversion of dryland to irrigable land is done by converting a composite dryland acre to a composite irrigable acre. The composite acre consists of a portion of an acre from each land group. An acre brought into irrigation will use only a portion of a dryland acre for each land group and produce only a portion of an irrigated acre for each land group.

Cost Elements

Irrigation costs can be broadly divided into fixed and variable costs. The fixed costs are dependent on the irrigation system in use. The fixed costs will be included in the irrigation rotation costs. The changing mix of systems over time will result in the fixed costs changing over time. Because a composite application system will be used, the fixed costs will be constant across all rotations in a given producing area and only one irrigation system is required for all land groups and rotations. Levies for surface water are also a fixed cost.

The variable costs of irrigation will be included in the water application activity. Groundwater and surface water costs will be different because of the costs associated with lifting the groundwater. The costs associated with increasing water depths, due to extracting more groundwater than what is recharged, are included in the water depletion activity. This cost is the incremental cost of drawing down the water level. For a given year this cost would change very little because the water depth would change very little. However, in tracking the water depth over time the cost associated with water depletion would increase as depth to water increased.

The costs associated with exporting and importing water will include the costs of structures, pumping, and revenues from (or charges for) the water. There is no direct cost associated with allowing water to flow out of the producing area into another producing area along its natural path.

The cost of converting dryland to irrigation land will consist of development costs. This may include ditching, leveling, test drilling, and start-up costs. The cost would not include well costs or system costs as these are included in the fixed cost component.

Information Available

Groundwater

To determine right-hand-side values of groundwater, three types of information are needed. The first and most obvious is the amount of water available. Available groundwater can be either a flow or stock resource. Dependable groundwater supply is based on the flow aspect of ground water. Recharge rates, less exogenous withdrawals of groundwater, will determine the dependable groundwater supply. Exogenous withdrawals include groundwater already withdrawn to meet non agricultural demands and exogenous agricultural demands met by groundwater. To estimate dependable groundwater compute:

$$RR - TGW_1 \times (1 - \frac{GWI}{TGW_2}) - EAD = GWDD$$

Where:

TGW_1 is total groundwater withdrawn, SNWA, Table III-1,

TGW_2 is total groundwater withdrawn, 1980 USGS water survey,

GWI is groundwater withdrawn for irrigation, 1980 USGS water survey,

RR is the recharge rate,

EAD is exogenous agricultural demand of groundwater, and

GWDD is dependable groundwater (Figure 2).

The amount of recharge which occurs can be determined for most PA's from the Second National Water Assessment (SNWA). For those other PA's United States Geological Survey (USGS) data augments that of the SNWA for recharge estimates. Total recharge for PA's is used because recharge to individual aquifers is not always given, the aquifers from which exogenous withdrawals come is seldom estimated, and because some excluded aquifers (as an irrigation supply) do supply some water for irrigation. More is explained on inclusion and exclusion of various aquifers later, but one final point on why including total recharge may not overestimate dependable supply. Obviously some excluded aquifers will not have all of their recharge withdrawn. But other excluded aquifers may have exogenous withdrawals depleting their supply. Unless suspected otherwise, recharge from nonincluded aquifers will be less than or equal to withdrawals. As a stock resource, no comprehensive estimate has been undertaken but the USGS has compiled regional and state studies in some areas especially those areas where ground water shortages are most severe. The SNWA fails as an information source for groundwater in that it gives the sum of storage potential of all aquifers for each PA. Storage potential does not mean that the water exists. This value is also inadequate in that it may include a large volume of water of inferior quality. Not only would water of too high salinity be of inferior quality for irrigation, but so would the water in aquifers with low pump yield rates. And also, the SNWA has no land area associated with it.

To determine the volume of groundwater in storage suitable for irrigation, estimates supplied by the USGS were used for the appropriate aquifer(s) for each producing area. One such source USGS HA-0648, is a map of saturated thickness contours of the highplains aquifer. By using this map, a planimeter, and Table I, the estimates on Table II were obtained. Table II shows the square miles of the parts of PA's lying in the listed states underlain by the highplains aquifer. Given these areas, their corresponding saturated thickness range, and the total volume of saturated material in each state, average saturated thickness can be given for the relevent producing area's. By assuming an average storage coefficient of .15 (see USGS HA-517, HA-516, HA-416, HA-515, HA-521, and HA-429) the volume of stored water is then determined.

Some of the aquifers excluded from ground water supply do supply water for other forms of consumption other than irrigation or may have an occasional pocket where well withdrawal rates are great enough for irrigation. Ideally, we would like to include these land areas and water volumes. No one knows the extent of these pockets. However, bias from these areas should be minimal not only because they are small compared to the total, but because some of the included aquifers have pockets where water is of inferior quality. Not being able to subtract out the area associated with these included pockets offsets (to a greater or lesser degree) the bias from the non-included areas.

Another type of aquifer that has not had its stored volume included are the valley fill aquifers - those sandgravel aquifers next to valley streams. Inclusion of these aquifers in the irrigation network would lead to biases. Generally these wells are shallow (hence would raise the average depth to water biasing pumping cost downward) and they are used mostly to augment surface irrigation. Because of their close interchange with surface flow, these sources of water would more accurately suit our purposes by inclusion in surface supply.

The second type of information needed is the land surface area where groundwater irrigation is possible. This area has been referred to already and is given in Table II. A further manipulation of this data will eliminate nonfarmable land included in the given table before the right hand side acreage restriction is determined. We assume nontillable land to be independently distributed with underlying ground water so that we need only to find that portion of land nontillable for the given area and subtract it out.

To update this acreage restriction, a third type of information is needed. As water is depleted and water tables fall, some area will no longer be irrigable. Information such as that in Table II will allow updating by giving surface areas corresponding to the various saturated thickness intervals. As water is mined, the surface of the aquifer is calculated as being lowered evenly over all. The irrigable acreage limit will decrease as the water table falls with areas of the shallowest saturated thickness affected first.

Due to the specific nature of the last two data types mentioned, the SNWA can provide no help. With energy needs being a very important part of determining water use, knowing the dynamics of water use and mining becomes very important. Measurements on the saturated thickness of aquifers is not easily collected so, not surprisingly, data is incomplete. However, best use has been made of the data available. Since the best available data corresponds to the more crucial areas, the accuracy should be greatest where it is most needed.

Table I. Distribution and volume of saturated material, high plains aquifer, 1980

State	Area of High Plains aquifer within state (square miles)	Percentage of area within each saturated thickness interval							Volume of saturated aquifer material (Millions of acre -feet)
		0-100 feet	100-200 feet	200-400 feet	400-600 feet	600-800 feet	800-1,000 feet	1,000 1,200 feet	
Colorado-----	13,870[1]	74	19	7	--	--	--	--	750
Kansas-------	27,750[2]	62	24	13	1	--	--	--	2,000
Nebraska-----	64,400	14	21	29	22	10	3	1	14,000
New Mexico---	7,110[3]	85	15	--	--	--	--	--	320
Oklahoma-----	7,350	58	25	11	6	--	--	--	610
South Dakota-	5,290	44	13	25	18	--	--	--	700
Texas--------	36,080	61	25	14	--	--	--	--	2,500
Wyoming------	8,190	46	22	18	4	4	1	1	920
TOTAL------	169,940[4]	44	23	19	9	4	1	--	21,800

[1]Excludes 1,000 square miles with little or no saturated thickness given in original.

[2]Excludes 3,200 square miles with little or no saturated thickness given in original.

[3]Excludes 2,600 square miles with little or no saturated thickness given in original.

[4]Excludes 7,000 square miles with little or no saturated thickness given in original.

Table II. Area above aquifers in the Great Plains

	Nebraska's ASAs				
Saturated thickness	1008	1010	1007	Total	Table I
1000-1200	498			498	644
800-1000	1557		109	1666	1932
600-800	6244		218	6462	6440
400-600	13530	31	623	14184	14168
200-400	12238	5185	1783	19206	18678
100-200	6571	4173	2803	13547	13524
0-100	2024	4873	1713	8610	9016
TOTAL	42662	14262	7249	64173	6440

	Colorado's ASAs					
Saturated thickness	1007	1010	1102	1103	Total	Table I
200-400	16	833			849	892
100-200	1090	1744	62	19	2915	2677
0-100	3542	3379	1829	2258	11008	11301
TOTAL	4648	5956	1891	2277	14772	14870

	Kansas's ASAs			
Saturated thickness	1010	1103	Total	Table I
400-600		529	529	310
200-400	8	3651	3659	3726
100-200	1977	4780	6757	6520
0-100	7839	11748	19587	10493
TOTAL	9824	20708	30532	31050

	New Mexico's ASAs					
Saturated thickness	1105	1205	1204	1304	Total	Table I
100-200	31	265	1144		1440	1456
0-100	2725	3566	1518	397	8206	8253
TOTAL	2756	3831	2662	397	9646	9710

Table II. Cont.

Oklahoma's ASAs

Saturated thickness	1103	1106	1105	TOTAL
400–600			441	441
200–400			808	808
100–200			1838	1838
0–100	358	413	3492	4263
TOTAL	358	413	4623	3492

Wyoming's ASAs

Saturated thickness	1005	1007	TOTAL
1000–1200		82	82
800–1000		82	82
600–800	148	328	180
400–600	125	328	203
200–400	54	1474	1420
100–200	78	2129	2051
0–100	755	3767	3012
TOTAL	1160	8260	7030

Texas's ASAs

Saturated thickness	1204	1203	1106	1105	TOTAL
400–600					0
200–400		237	241	4573	5051
100–200	506	3227	1464	3823	9020
0–100	8104	5772	5153	2980	22009
TOTAL	8610	9236	6858	11376	36080

<u>Surface water</u>

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). This information source is not 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, The SNWA does not indicate 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 <u>Current Streamflow Supply</u> (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. Since we will use the SNWA's projection for consumption from the nonagricultural components, their origin will be of little circumstance as a surface component. 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.

CSS includes the groundwater withdrawn for livestock. This quantity must be subtracted from CSS to prevent overstating dependable surface water supply (Tabler I - III, SNWA).

The groundwater used for irrigation is considered part of CSS. As mentioned before, this component must be taken out. The SNWA does not give groundwater use for irrigation 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.

Instream water needs of 30 percent of average flow will be assumed. 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 the 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 must also be subtracted from CSS to determine the water available to agriculture.

$$CSS - NAU - EXL - [TGW \times \frac{GWI}{TGW_2}] - [30\% \text{ of } (ATS \pm TRNS)] \text{ vs } T\&C = SW$$

CSS is current streamflow supply, Table IV-4, SNWA,

NAU is exogenous uses Table IV-3, SNWA

EXL is assessed livestock demands, TAble IV-3, SNWA,

TGW is total groundwater withdrawn, Table III-1, SNWA,

GWI is groundwater withdrawn for irrigation, 1980

TGW_1 is USGS Water Survey, total groundwater withdrawn, SNWA, Table III-1,

TGW_2 is total groundwater withdrawn, 1980 USGS Water Survey,

ATS is assessed total streamflow, Table III-5, SNWA,

TRNS is transfers, add exports, subtract imports, Table II-2, SNWA,

vs is versus, select the large of the two,

T&C is treaties and compacts, Table III-3, SNWA, and

SW is surface water available to agriculture.

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, more precisely, we have:

$$CSS - \Sigma NAU - \Sigma EXL - \Sigma(TGW, x \frac{GWI}{TGW_2}) - \left\{ [30\% \text{ of } (ATS \pm \Sigma TRNS)] \text{ vs } T\&C \right\} = SW$$

where variables are defined as before and Σ is the summation over upstream and the current PAs.

Not all agriculture water consumption will be endogenous. Those which are exogenous must have their consumption 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 production. 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."

To project surface water supplies available to agriculture for 1985 and 2000, two 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. And second, increase in nonagricultural consumptive demand for water must be subtracted out of (and decrease added in to) CSS.

Land constraint

The land irrigable with surface water must be constrained to prevent the model from diverting water from a surface source, such as a river or lake, to canals that do not exist. The land constraint will be based on current acres irrigated with surface water sources. The 1978 Census of Agriculture contains estimated quantities of water and areas irrigated by water source. In 1978, of the 50 million acres irrigated, approximately 23.5 million acres were irrigated with on-farm and off-farm water sources. These water sources are primarily surface water. The acreage restriction would therefore be the acres irrigated with onfarm and off-farm water sources. The addition of new publically funded projects will increase the surface acres irrigable in these producing areas. The present information on these projects will allow a fairly accurate projection of additional acres because most projects to come on line in the next 50 years have already had monies appropriated either for building or design and planning.

Restricted Model of Surface Water Supply

The restricted model is based on the assumption that present water rights have locked in the pattern of surface water use. This model specification requires the surface water supply for a producing area to be determined by past use levels. These quantities of water will be derived in two ways. The first way is to use the irrigated acres in the 1978 Census of Agriculture and irrigation water use coefficientss (Soil Conservation Service, 1976) to obtain an estimate of the total quantity of irrigation water used for a producing area. The 1978 Census of Agriculture can be used to verify the quantities estimated. The water used by exogenous crops will be taken out of the total, leaving water used by the endogenous crops. Endogenous crop water use next must be split into groundwater and surface water. Estimates of the proportions of groundwater and surface water used in irrigation can be obtained from the 1978 Census of Agriculture and from U.S. Geological Survey estimates. The quantity of surface water for use in endogenous crop production will be the endogenous crop water used times the proportion of surface water used for irrigation. It is the quantity of surface water used in endogenous crop production that is used to constrain surface water supply in the restricted model of surface water supply.

Exogenous water uses, Industrial, Commerical and Residential

Exogenous water uses are from the Second National Water Assessment. Supply effects are outlined in the previous sections on groundwater and surface water supplies.

Crops and livestock

Exogenous irrigated crop acres will be obtained from NIRAP projections. The exogenous crop irrigation water use will be the exogenous crop acres times the water use coefficients developed by the Special Projects Division (1976) of the Soil Conservation Service.

The exogenous livestock water use is derived from a number of sources. Livestock production projections will be obtained from NIRAP.

The water use per animal is obtained from the coefficients developed by the Special Projects Division (1975) of the Soil Conservation Survey.

Elements

Water use coefficients for irrigated rotation will be obtained from the EPIC model. The EPIC coefficients must be adjusted to take account of application losses. Estimates of application losses will have to be obtained from personal communication with irrigation engineers in the various regions of the United States as this type of information is not published. Incidental consumption losses developed by the Special Projects Division (1976) of the Soil Conservation Survey could also be used.

Water losses during conveying water from the source to the field will be obtained from the estimates developed by the Special Projects Division (1976) of the Soil Conservation Service. The conveyance losses in the report must be split into groundwater conveyance losses and surface water conveyance losses. Data on proportions of groundwater and surface water used in irrigation will be obtained from the 1978 Census of Agriculture and from the U.S. Geological Survey.

The element in the acreage constraint will have the value of one in the majority of situations. A value greater than one would indicate a portion of the land can not be irrigated, such as the corners for a center pivot system. These dryland segments need to be taken into account to prevent areas from being irrigated where there is not a supply of water. These values will be determined by the irrigation system in use and by the water source. For each irrigation system the total acres required to have one irrigated acre will be determined (1.203 for a center pivot designed to irrigate a 133 acre circle). Surface water supplies should have the area the canals cover accounted for but this type of information is not available. Finally, the losses are weighted for each system to obtain the coefficient for the producing area as a whole.

The conversion of land from dryland to irrigated land will be a composite of several land groups. This method is preferred because the tract of land will not consist of only one land group. Also, model size considerations are such that one conversion activity for all land groups is preferred to one activity for each land group. The conversion of range and pasture to cropland is handled in a similar matter (PAC meeting Oct. 14-15, 1982). The composites will be determined from the 1982 NRI data.

Costs

Irrigation costs will be determined for seven irrigation systems; high pressure center pivot, low pressure center pivot, hand move, mechanical move, gated pipe, siphon tubes, and flooding. The coefficients required to calculate the costs are based on the Oklahoma State University irrigation cost program. Because a composite system is used to apply irrigation water, these costs are weighted by systems reported in the 1978 Census of Agriculture to obtain a composite cost. The procedure allows the weights to be changed over time to reflect the changing mix in application systems. The fixed costs of the composite system are added into the rotation costs while the variable costs are used in the application activity.

The costs of groundwater and surface water application will be calculated by the same program. The cost differences between the two are the following; groundwater costs include higher pumping costs because the water is pumped out of the ground, groundwater costs include the fixed cost of the well and related equipment, and surface water costs include a water charge paid to the water supplier. Information on the pumping depth for groundwater is available in the 1978 Census of Agriculture. Information on surface water charges are given for some areas in the 1978 Census of Agriculture and the remainder will have to come from personal communication with individuals familiar with those areas.

The water depletion costs are the additional cost incurred over time from a declining groundwater level. These costs are the additional costs associated with pumping water from a deeper depth. The added cost for the extra pumping lift will be calculated by the cost program previously referred to. The additional pumping depth used will depend on the expected drawdown during the year. A number of depletion activities could be used, each reflecting a specific range of water decline.

APPENDIX A

Assumptions

Figures A.1 thru A.3 attempt to show the conditions or nature of water exemplifying the complications and the need for assumptions to quantify it. These following criteria must be kept in mind to understand why these assumptions were made. First, since the CARD model deals with information aggregated over an entire PA, specific characteristics of water use, quantity or storage could not be explicitly included. Secondly, data which is available often does not pertain specifically to our needs. And finally, just as water shows a complex inter-relationship so must the assumptions made about it implying that the assumptions balance with each other.

The following is a list of basic assumptions was an attempt to point out the assumptions. By examining all assumptions at once it is hoped that a better understanding and evaluation of water quantity estimations can be made.

Asssumptions on ground water supply

1. The present ratio of ground to total water withdrawn is assumed to be exemplified by the 1980 USGS Water Survey data.
2. Aquifers classified as usable for irrigation have parts which are not usable (over estimating land area) just as those aquifers not usable for irrigation will have some parts which are suitable for irrigation (not included land area). These two area types are assumed to approximate each other.
3. When water is drawn down in the aquifer, the water table is assumed to drop evenly throughout the PA.

4. The aquifer is assumed to have a "bowl" shape (see Figure A.2). Thus, as the water table drops, some land loses its irrigtion potential.

5. Aquifers within close proximity of surface flows act more as a resevoir for streamflow. Their draw down behavior, their depth to water, and their close relationship with surface flow gives them characteristics which do not compare to other aquifers usable for irrigation. We do no include them as groundwater supply. If a significant amount of irrigation does come from such aquifers, it would be better to include these by augmenting the surface supply.

6. Aquifers are assumed to have salinity vary directly with depth.

7. Recharge rates are assumed to remain at current estimated rates.

8. Future increase in exogenous agricultural water demands are assumed to be met from ground water supplies unless specific cases are known where surface water will be used.

9. A storage coefficient of .15 is assumed based on data given in USGS HA-416, HA-429, HA-515, HA-516, HA-517, HA-521, and HA-529.

10. The net effect of not including stored ground water unsuitable for irrigation (though it may be mined by municipalities) but including all aquifers recharge rates (though some may have little water withdrawn) is assumed to be zero.

11. Groundwater used in irrigation is assumed to not enter any surface flow

Assumptions for surface water supply

1. Future increases in exogenous consumption other than in agriculture are assumed to be withdrawn from surface sources unless known groundwater withdrawal will occur.
2. The ratio of groundwater withdrawn for irrigation to total groundwater withdrawn from the 1980 USGS Water Survey is assumed to estimte the same ratio for the SNWA data.
3. Groundwater mining will not reduce streamflow.
4. Streamflow from dry conditions is of a small enough quantity to allow full utilization of that volume of water on an annual basis.

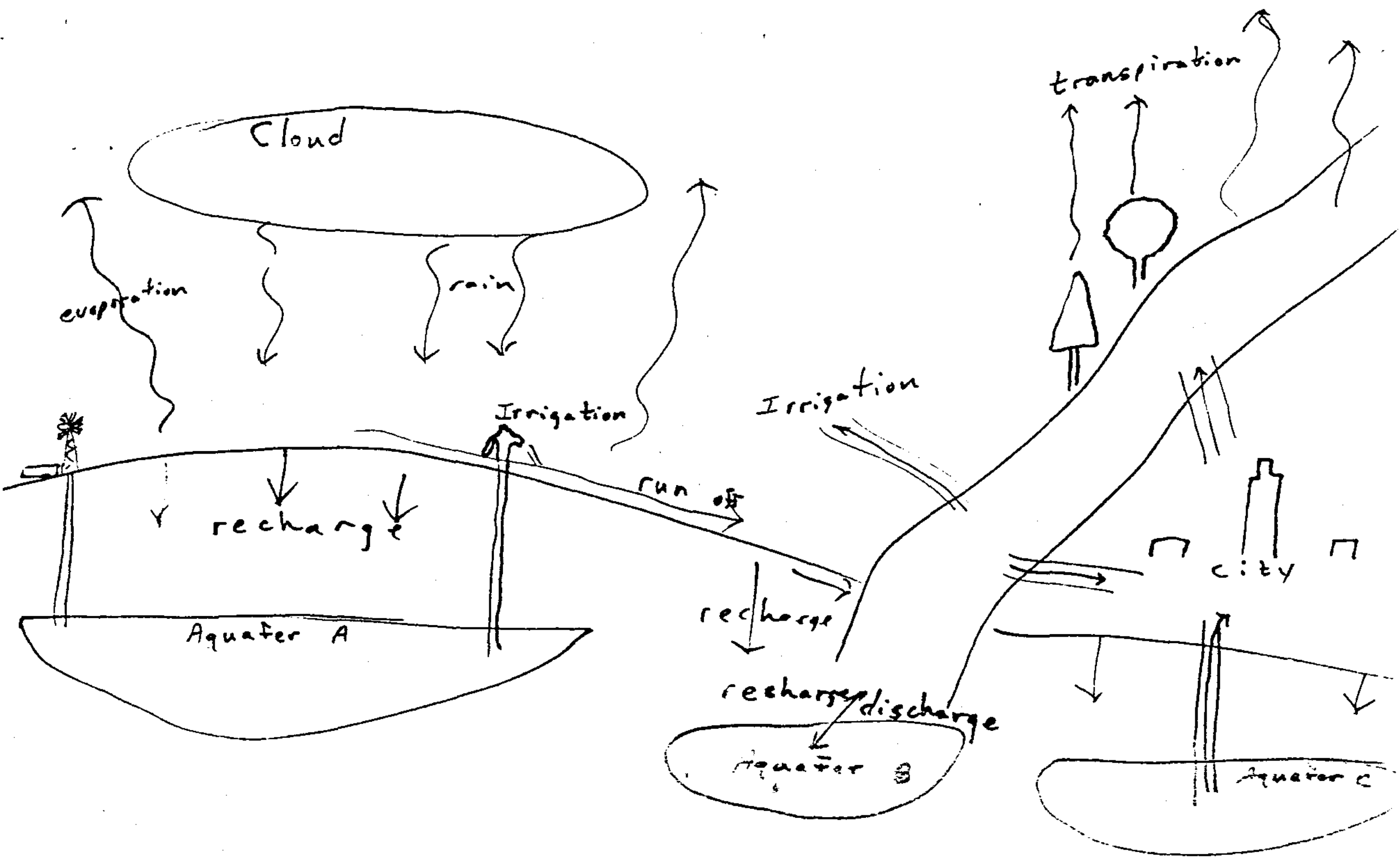
Cloud
evaporation
rain
transpiration
Irrigation
Irrigation
run off
recharge
recharge
recharge
discharge
city
Aquafer A
Aquafer B
Aquafer C

Figure A.1

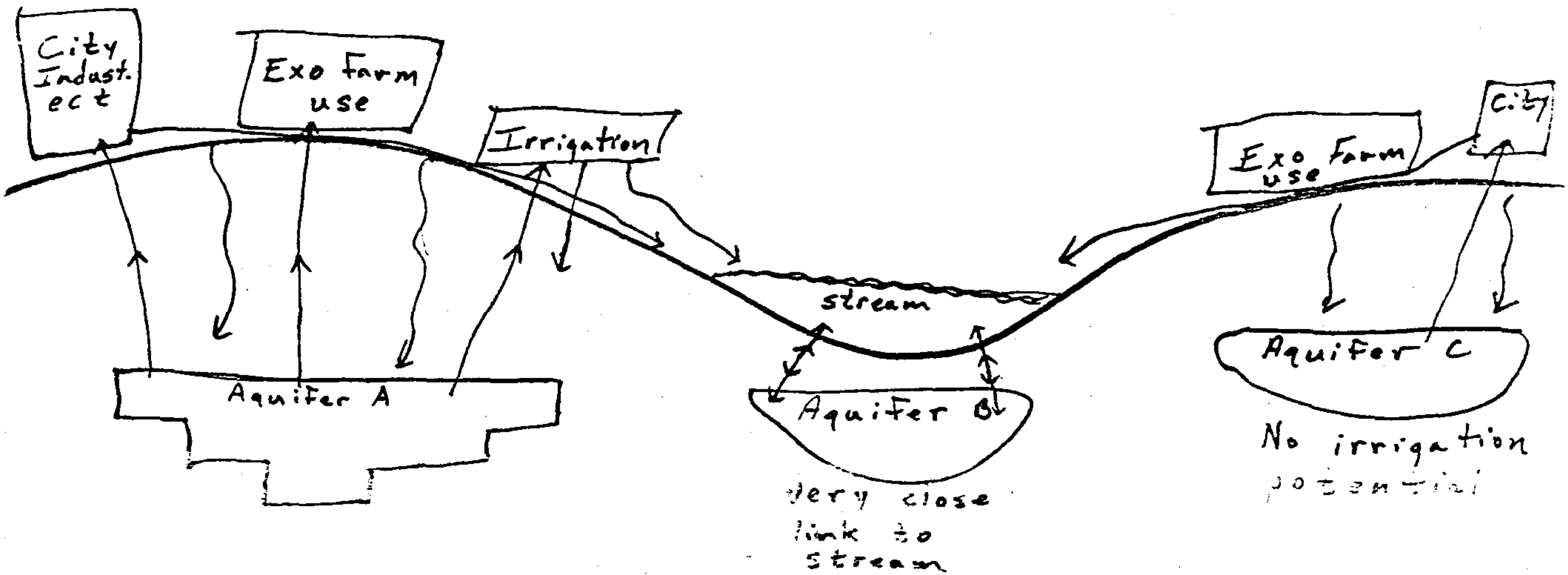

Figure A.2 Groundwater

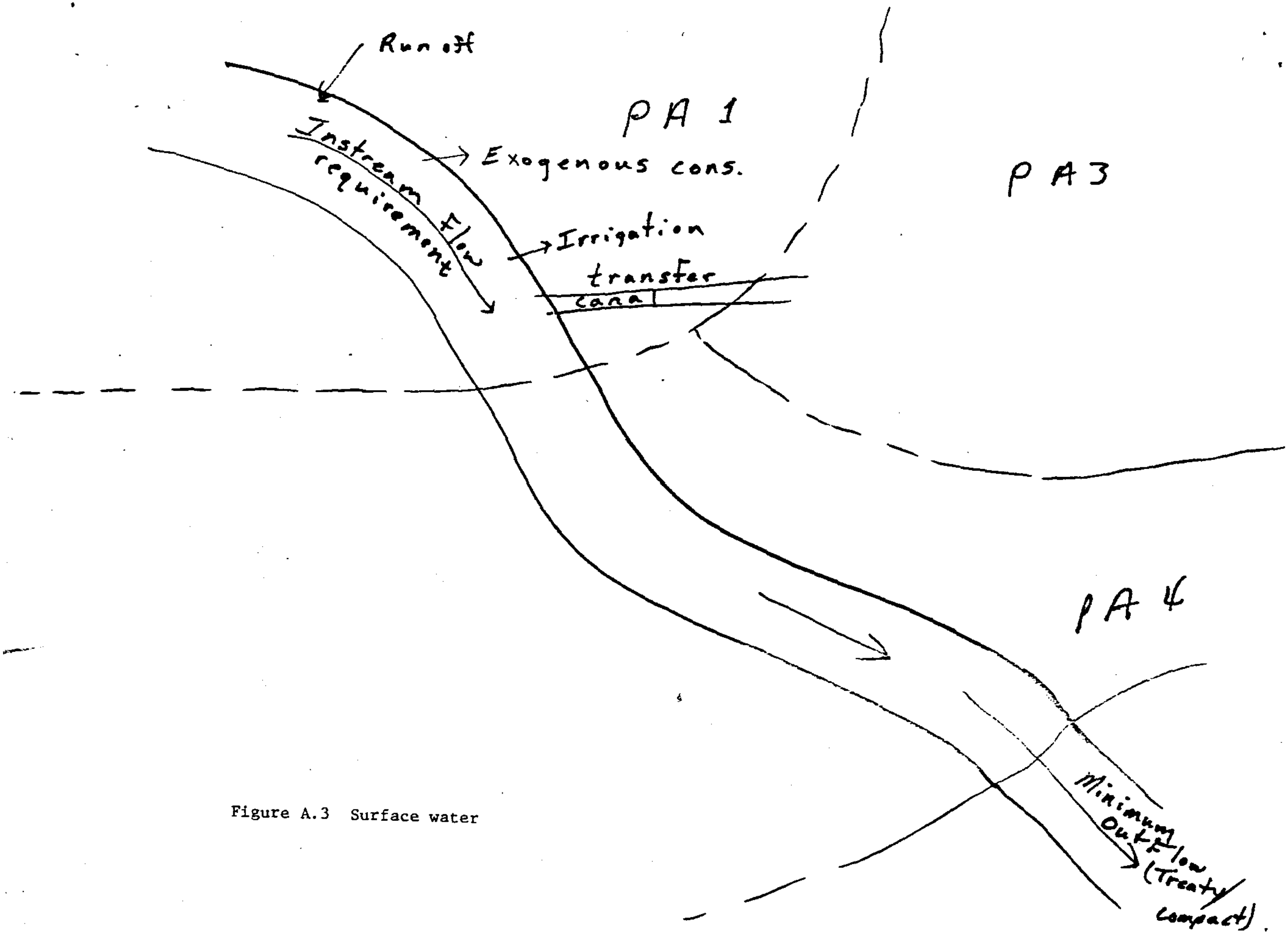

Figure A.3   Surface water

APPENDIX B

An Example of Aggregate Subarea 1103 (Producing Area 63)

Development of the right hand side (RHS)

Groundwater required and surface water required are accounting rows so will have a RHS value of 0.0

Groundwater dependable is 1421 million gallons daily (gmd) (SNWA, TAble II-1). This converts to 1,700,000 acre feet. Exogenous crops used 428 acre feet of water in PA 63. This value was obtained from multiplying exogenous crop acres (1978 Census of Agriculture) by the crop consumptive irrigation requirement (Special Projects Division (1976) of the SCS). The groundwater use is 95.53 percent of total. Therefore 409 acre feet of water would be taken out of the dependable groundwater supply.

Groundwater depletable is obtained from calculating the total volume of saturated material in the PA. The total volume is 1,790,000,000 acre feet. Applying a storage coefficient of .15 will yield 269,000,000 acre feet of depletable groundwater.

The total surface area above aquifers in PA 63 is 23,343 square miles, or 14,939,520 acres (Table II). This value presently overestimates the acres irrigable with groundwater because it contains topography which may not be irrigable and it contains saturated thicknesses that are too shallow for irrigation pumping. Acres not irrigable because of topography will be calcualted as a proportion of land in specific land classes from the 1982 NRI. To account of the shallow saturated thickness levels a method is going to have to be derived to determine the area where the aquifer is thick enough for irrigation. A proportion based on saturated thickness is a possible approach. Finally, in 1979 there were two million acres irrigated with groundwater in this PA plus another 80,000 acres used both ground and surface water.

There were 410 exogenous crop to be subtracted from the total. Surface water supply for the flow model requires a number of computations.

CSS = 4634 mgd

Σ NAU = 297 mgd

Σ EXL = 52 mgd

$$\Sigma \left(TGW_1 + \frac{GWI}{TGW_2}\right) = 3619\ (.8696) + 217\ (.1693) = 3184 \text{ mgd}$$

30% of ATS = 1433 mgd

T&C = 0

Therefore: SW = 4634 - 297-52-3184-1433 = -332 mgd. Converting this to acre feet will yield -371,840 acre feet. Exogenous crop water use is subtracted from this total. In 1978, the exogenous crop water use was estimated to be 19 acre feet, resulting in a surface water supply of -371,859 acre feet. The negative surface water supply raises several questions about the values in the

SNWA. The most obvious one is the 30 percent of assessed total streamflow required for wildlife. A second concern is the use of the dry conditions current streamflow supply.

Surface water supply for the restricted model formulation was calculated in the following way. Total crop irrigation requirements for all crops was calculated from irrigated acres (1978 Census of Agriculture) and crop consumptive irrigation requirements (Special Projects Division, 1976, SCS). Total crop irrigation requirements were 1,929,143 acre feet, of which 4.47 percent was taken as surface water (USG-S2, 1980). Surface water crop requirements are 86,223 acre feet and taking application losses into account (25 percent) resulted in total surface water use of 114,977 acre feet. [The 1978 Census of Agriculture reported that 36,933 acre feet of surface water was applied in 1979].

Surface water acres are obtained from the 1978 Census of Agriculture for the year 1979. The 1982 NRI can be used to obtain this information when it is released. In 1979 there were approximately 13,000 acres irrigated with surface water only and 76,000 acres that used both groundwater and surface water. The RHS value will be bounded by these two values. Portioning water use to the two sources would give a surface water area of approximately 23,000 acres. Exogenous crop acres, equal to 19 in PA 63 is subtracted from the surface water acres.

The dryland acreage constraint is part of the crop sector and will not be addressed.

Development of the elements in the matrix

The vector A will be the crop consumptive irrigation requirement divided by (1- the application loss).

The element B will be 1.0 for groundwater and (1- conveyance loss) for surface water.

The matrices K and N, land requirements for each irrigated acre by land class, will be set equal to one.

The vectors F, E, and D will be determined from the 1982 NRI.

The element M has not been determined.

The irrigation costs

The costs of irrigation are composite costs of seven application systems. The fixed costs, which will be added into the irrigation rotation costs are \$24.47 per acre for groundwater and \$16.88 for surface water systems.

The application cost per acre foot of water for groundwater is \$78.91 per acre foot. The application cost for surface water is \$36.47 per acre foot. The cost of water depletion is \$.28 per foot of decline in the water level.

There are no exports or imports of water in this region so these activities can be dropped.

The costs of converting dryland to irrigated land have not been determined.