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INTERREGIONAL PLANNING OF WATER RESOURCES ALLOCATIONS BY SYSTEMS ANALYSIS APPROACH

A Summary Report

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PRWG100-5

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PREFACE

The following is a listing of publications and professional papers which have been derived from this study

Utah Water Research Laboratory Reports:

(1) Water Resources Planning to Satisfy Growing Demand in an Urbanizing Agricultural Region, by Thomas C. Anderson. UWRL Publication Number PRWG100-1, 1972. 29 p.
(2) Development of Regional Supply Functions and a Least Cost Model for Allocating Water Resources in Utah: A Parametric Linear Programming Approach, by Alton B. King, Jay C. Andersen, Calvin G. Clyde, and Daniel H. Hoggan UWRL Publication Number PRWG100-2, 1972. 162 p.
(3) The Economic Efficiency of Inter-Basin Agricultural Water Transfers in Utah. A Mathematical Programming Approach, by John E. Keith, Jay C. Andersen, and Calvin G Clyde. UWRL Publication Number PRWG100-3 1973. 136 p.
(4) Demand for Agricultural Water in Utah, by Mark H. Anderson, Jay C. Andersen John E. Keith, and Calvin G. Clyde. UWRL Publication Number PRWG100-4. Forthcoming.

Professional Papers

(1) Optimal Allocations of Water Resources in Utah, by Calvin G. Clyde and Alton B. King; presented before the American Society of Civil Engineering Hydrology Division Specialty Conference, 1971 Accepted for publication in the Journal of Hydraulics Division, ASCE.
(2) The Effect of Water Use in Great Salt Lake on the Jordan River Basin Water Allocations: A Systems Analysis Approach, by John E. Keith and Jay C. Andersen; presented before the 1972 Utah Section meeting of the American Water Resources Association and published in a proceedings report.
(3) A Systems Analysis Approach to Water Resources Allocations in Utah, by John E. Keith and Jay C. Andersen; presented before a meeting of the Utah Section of the Institute for Management Science in 1973.
(4) Determining the Economic Costs of Economically Non-Optimal Public Policy, by John E. Keith and Jay C. Andersen; presented before the 1973 Pacific Southwest and Intermountain Regional meeting of the American Association for the Advancement of Science.

The following report is a consolidation and summary of these papers and publications. It is UWRL Report number PRWG100-5.

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INTRODUCTION

Reason for Study

The problem of the allocation of water in Utah involves two considerations: (1) The allocation of water itself, and (2) the allocation of water-related resources necessary to distribute the water. Since relatively large investments of public funds and resources are contemplated to meet the needs for water in Utah, both by federal and state agencies, this study was undertaken to examine the availability of and the demands for, water in a systematic way.

The application of a supply and demand model for water in Utah appeared to be a reasonable conceptual framework for the study; the complexity of the problem dictated the use of mathematical programming techniques using computer technology. The results of the study were intended to determine the effectiveness of the approach as well as generate information and analyses useful to public decision-makers involved in water resource planning in Utah.

Study Objectives

The general objective of the study was to develop the methodology for determining optimal allocations of water in Utah, given alternative assumptions and constraints. The approach was to structure a statewide model of water use and delivery in a linear programming framework, explicitly including the water supply system, various demands for water, and alternative water salvage, reuse, and transfers under consideration by water planners. The optimal solutions to the statewide programming model were based upon maximizing net economic returns to water use in the state given alternative assumptions and were, therefore, the economically efficient allocations of Utah's water supplies.

There were six specific objectives of the study:

1. Determine the hydrologic characteristics and cost of water from various sources in each of the hydrologic study units of the state defined by the Utah Division of Water Resources.
2. Determine supply functions for water in each of the hydrologic study units (HSU) of the state, given the hydrology and costs of water.
3. Determine value of marginal product (VMP) of water in agricultural uses[1] (the largest water use by far) from crop production considering productivities of land classes, costs of crop production, and other pertinent data.
4. Determine demand functions for water in each of the HSU's of the state, from the available agricultural, municipal, and industrial data.
5. Determine the present economically efficient allocation of water among HSU in Utah, given the linear programming model's profit generating objective function and the physical and economic constraints of the supply and demand relationships.
6. Determine changes in these efficient allocations given alternative projections of demographic changes in Utah.

Given the determination of the efficient allocations over the projected time frame, the economic costs of prematurely investing in transfer facilities or of limiting the use of low-cost water sources were estimated using losses in producers' and consumers' surplus.[2]

Overview of the Study

The study was done in several "steps," each of which required considerable theoretical and empirical analysis. This report contains synopses of each of these steps and is necessarily lacking in full details. References to the detailed work are provided throughout the report.

The study was initiated by determining the sources of water (existing or potential) from statewide hydrological data. The marginal cost of using water from each of these sources was determined; existing facilities require operation and maintenance costs, and potential source require development, operation, and maintenance costs. These data were then translated into supply functions using linear and non-linear programming techniques.

The next step was to determine the productivity of agricultural land in each HSU, by land class (soil type) for

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[1] The value of the marginal product is the return to producers generated from the use of an additional unit of the resource in production.

[2] As defined by the area between the price and the marginal cost or supply curve, and the demand curve and price, respectively, for each unit of water up to the efficient allocation where supply equals demand. This is a measure of total welfare. See Mishan (1964) for an extensive discussion of consumers' and producers' surplus.

all the crops which would be grown in significant amounts. Then costs of production, except water, were subtracted from the revenues produced by each crop to yield a net return per acre. Fixing water inputs at alternative levels in a linear program allowed demand functions to be developed for water, based upon shadow prices and quantities (value of a unit of water).

The supply and demand relationships were then included in one programming model, which maximized net returns to water in agriculture, given municipal, industrial, and wetland (recreation, marshland, etc.) requirements. Alternative requirements which might be expected for future municipal and industrial growth were included so that the development of various water sources over time could be analyzed.

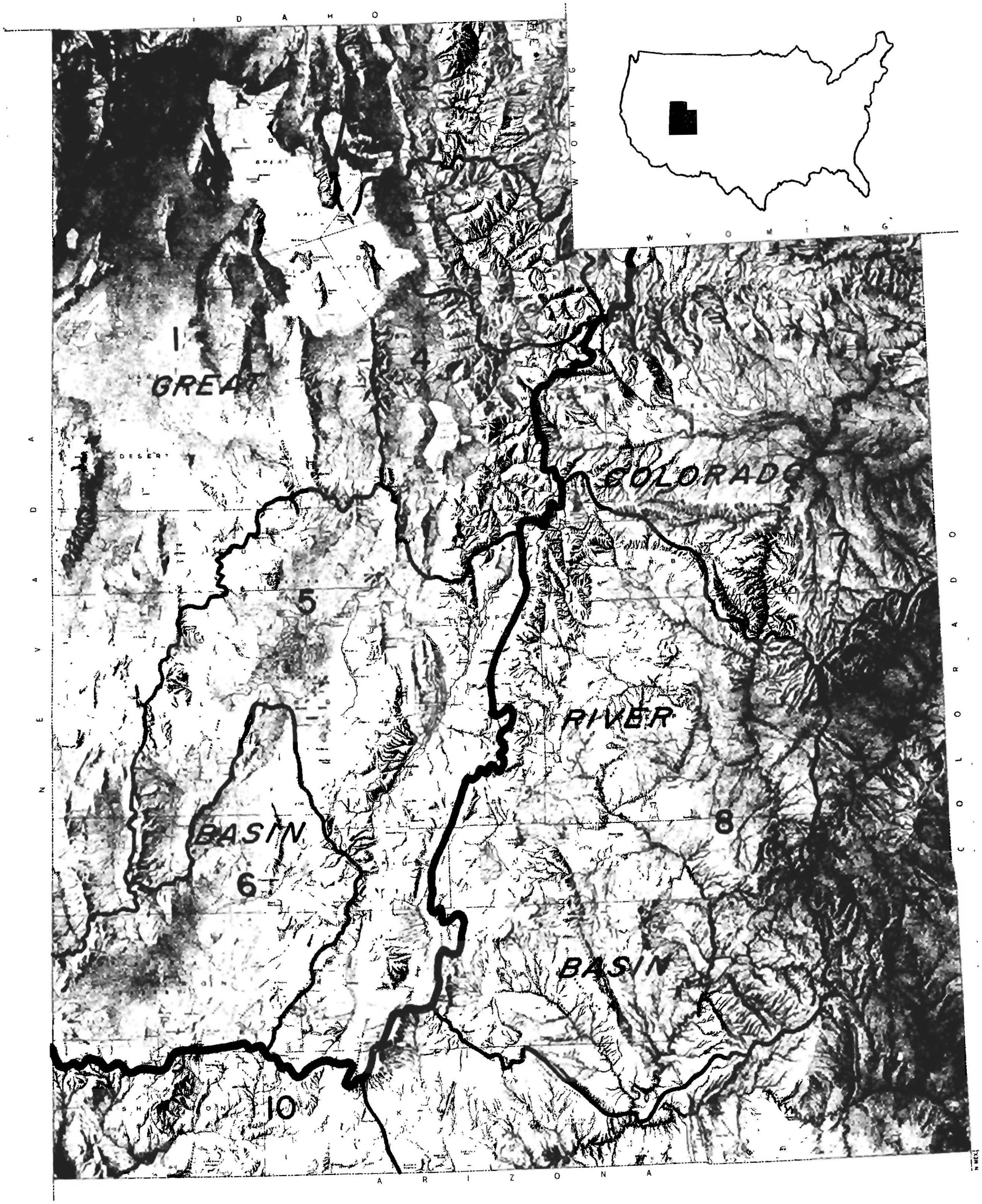

Figure 1. Map of hydrologic study units of Utah.

Table 1. Land use and water consumed in Utah.

Type of Land	Percent Total Area	Percent Water Consumed
Grazing land and watersheds	81.7	72.1
Arable but uncropped land used for grazing	2.6	1.9
Dry-farmed land	1.1	1.0
Irrigated land	2.1	4.6
Cities and towns, industrial sites	.5	.2
Wasteland, national parks, and monuments	9.0	6.4
Water area	3.0	9.5
	100.0	95.7
Outflow to interstate streams		4.3
		100.0

Source: McGuiness, 1963.

and outflow to interstate streams (McGuiness, 1963). The 7.7 percent is contributing directly to the livelihood and well-being of man and is considered an available controllable resource. The 13.8 percent is not considered as completely available. There are compact agreements involving the outflow of the interstate streams which must be included in any analysis of the states' resources. The evaporation losses from water surface areas occur predominantly from the Great Salt Lake. Policies and legal commitments concerning inflow to the lake must also be included in any analysis of the state's resources.

The manageable (wholly or in part) water, totaling 21.5 percent (7.7 + 13.8) appears in three forms: (1) Precipitation directly on the water and land areas, (2) surface runoff in rivers and streams originating in the watershed areas, and (3) groundwater in alluvial reservoirs and other aquifers which originated from percolation of precipitation and water bodies on the above ground surface and from groundwater interflow from the watershed areas.

Major water and related land resources problems

A number of inefficiencies in the present allocation of water in Utah are evident. While there is access to limited supplies of water for nearly two-thirds of its irrigated land, there are over two million acres of swamp land, marshes, mud flats, and valley bottoms currently saturated. In addition, water evaporation from reservoirs and lakes, as well as transpiration by phreatophytes amounts to far more than is withdrawn for public supplies. This may or may not be a misallocation when one considers the total environment. Herein lies the challenge for water planning and management in Utah (Utah Water and Power Board–Utah State University, 1963).

Despite water requirements existing in the state, as reflected by the more than three million acres of land in Utah that could be added to agricultural production if water were available and water necessary for industrial and urban growth in the state, a major share of Utah's portion of Colorado River water continues to flow out of the state and about 1½ million acre-feet/year of water is evaporated from the Great Salt Lake. This water was assumed to be within the manageable capacity of man, and analysis of economically efficient management was indicated.

Maximum development of Utah's vast groundwater reservoirs will require changes or at least most realistic interpretations of present state statutes in harmony with natural hydrologic relationships. In the past, well owners have commonly held the view that their rights involve a guarantee by the state to maintain given water pressures or water table levels in wells. Such restrictions, though physically possible, would limit the use of groundwater to a fraction of the amount available in storage. Recent court decisions indicate that some change in this condition is imminent. Likewise, problems of water quality are intimately interwoven with other development problems, and require careful consideration.

Hydrologic characteristics

Knowledge of the physical availability of water is required in order to begin a study of allocations. Thus, the hydrology of Utah is the basis for a systematic analysis. A more detailed description of Utah's hydrology is available in King et al., (1972).

Available resources

There are four basic sources of water that may be more fully developed to provide for future requirements in Utah (Haycock, 1968):

1. Water resources along the Wasatch Front including Bear River. This means utilization of water currently evaporated from the Great Salt Lake
2. The Virgin River and minor streams draining into the lower Colorado River.
3. Groundwater basins within the state.
4. Upper Colorado River water allocated to Utah

Streams within the state have been measured or gaged extensively and surface-water availability is well defined

Although there already has been considerable groundwater development in Utah, extensive groundwater supplies remain available Water available for development in each HSU is presented in Table 2.

One of the state's greatest sources of undeveloped water is in the Upper Colorado River Basin separated from the most significant population growth areas by the Wasatch Mountains. Because of this separation of present growth areas from potential supply, much of Utah's share of the Colorado River water currently flows out of the state unused. Even if a sizeable amount of Upper Colorado River Basin water is transferred to the Great Basin by the Central Utah Project a large scale project of the U S Bureau of Reclamation, approximately a third of Utah's share of this water will still be unused (Haycock, 1968) Other projects would be necessary to fully utilize this supply

Several other means by which available supplies can probably be increased include control of phreatophytes and evaporation, saline water conversion, waste water reclamation and reuse, and better watershed management Weather modification and importation schemes also may eventually provide additional supplies.

Return flows

Not all of the water diverted to agriculture is consumptively used by the crops. That part which is not consumptively used runs off the cropland as surface flow

Table 2. Available water resources in Utah (basin yield).

	Water Availability		
Hydrologic Study Unit	Groundwater (ac-ft/yr)	Local Surface Water (ac-ft/yr)	Local Surface Water Plus Groundwater (ac-ft/yr)
1	187,000	613,000	800,000[a]
2	138,000	917,000	1,055,000[b]
3	65,000	660,000	725,000[c]
4	394,000	560,000	954,000[a,d]
5	356,000	417,000	773,000[e]
6	130,000	80,000	210,000[a]
7	40,000	1,319,000	1,359,000[f]
8	--	650,000*	650,000[a]
9	----	430,000*	430,000[a]
10	10,000	250,000*	260,000[a]
Total	1,320,000	5,896,000	7,216,000

*Much of this water considered as available for transfer

Source

[a] Utah Division of Water Resources, 1970.

[b] Utah State University Utah Division of Water Resources 1972

[c] Utah State University Utah Division of Water Resources 1970b

[d] Utah State University Utah Division of Water Resources, 1969

[e] United States Department of Agriculture - Utah Department of Natural Resources, 1969

[f] Utah State University Utah Division of Water Resources 1970a

or seeps into the ground, and is known as return flow. Some of the water which seeps into the ground becomes part of the water called "inter-flow" in the water budget studies and essentially is available as surface water since streams, lakes, and reservoirs intercept it. The remainder becomes part of the groundwater supply by the process of deep percolation. Return flow coefficients, K_{RF} (shown in Figure 3) have been determined from existing water budget studies by comparing inflows with outflows from each use. When multiplied by the diversion, the return flow is determined as below:

$$\text{Return Flow} = K_{RF} \text{ x Agricultural Diversion}$$

Coefficients were determined separately for return flow to surface water and for return flow to groundwater for each of the ten HSU's.

Likewise not all the water diverted for municipal and industrial use is consumptively used. Wastewater from residential sewage and industrial plants after treatment is channeled into surface streams, and is also known as return flow. This water is available for use again. Return flow coefficients have been determined from water budget studies for each of the ten HSU's. As is the case for agriculture, the return flow is determined from the product of the coefficient and the diversion as shown below.

$$\text{Return Flow} = K_{RF} \text{ x Municipal and Industrial Diversion}$$

Storage requirements

Storage requirements, including amounts needed to adjust seasonal fluctuations in stream flow as well as long-term carryover needed to meet extended series of dry years, were estimated for each of the ten HSU's.

Estimates of long-term carryover storage requirements are based upon the results of frequency mass-curve analyses completed for 76 streams located throughout the state and published in the "Hydrologic Atlas of Utah" (Utah State University–Utah Department of Natural Resources, 1968). A frequency mass-curve is obtained by plotting for any selected probability of occurrence, the expected values of accumulated volumes of runoff during each of many sequences of consecutive months (through several years) against the carryover period in months. Separate frequency mass-curves are obtained for each probability of occurrence selected.

Since the volume of required storage can be considered a function of probability of not experiencing a shortage, carryover period, and demand level, frequency mass-curve analysis provides information necessary for plotting draft demand vs. storage curves. A computer program developed to carry out the large amount of computation involved (Jeppson, 1967) was used to analyze monthly runoff data and provide the information necessary to compute draft vs. storage for the 76 streams

Table 3. Return flow coefficients.

	Agricultural Use		Municipal and Industrial Use
HSU	To Surface	To Ground	To Surface Only
1	.4742	.0500	.7000
2	.6077	.0500	.6600
3	.5833	.0500	.4366
4	.5609	.0500	.6889
5	.6250	.0500	.4588
6	.4947	.0500	.6923
7	.6288	.0000	.6500
8	.6250	.0000	.3000
9	.8000	.0000	.2500
10	.5000	.0000	.3000

Source: Same as Table 5.

considered in the Hydrologic Atlas. Draft was in percent of mean annual flow for values of 50, 65, 80, 95, and 110 percent. Storage was given in inches over the watershed. Probability values (probability of not experiencing a shortage) of .75, .90, and .95 were used.

The long-term storage required corresponds to the maximum values of storage as a function of the carryover period. These values were determined for each of the streams at each of the five draft values and three probability levels. The seasonal storage was determined for each HSU by calculating the difference between the supply curve on a monthly basis and the draft requirement for each of the five draft values. Where water budgets were not available, the draft curves were based on calculations using Munson's Index (Munson, 1966). Both the total long-term storage and seasonal storage were based on monthly stream flow data from the Hydrologic Atlas weighted for the watershed area. The seasonal storage was added to the long-term storage to determine the total storage required for HSU 2 through 10. Insufficient stream flow data were available for HSU 1 to perform this type of analysis (graphic figures available in King et al., 1972).

Groundwater recharge potential.

The groundwater recharge potential or opportunity was assessed in each HSU in order to define the recharge constraint. The problem was to designate the areas where artificial recharge to the groundwater basin is practicable, provided the water table is low enough to permit recharge, and to estimate for each area the amount of water that could be put underground in basins and/or through wells.

In HSU 2, 3, and 4, the reservoirs are essentially alluvial fans intermingled with and overlapped by lake bottom sediments of Pleistocene Lake Bonneville. Recharge to these reservoirs is largely at the apex of the alluvial fans where the stream gravel is coarse, and where lake bottom sediments, deposited over the fan during high stages of the lake, have been stripped away by the stream after the lake lowered. These are limited areas near the mouth of canyons from which the fan material came. Based on results of the few artificial recharge experiments conducted in Utah, a possible recharge rate of 2 feet per day for 300 days of the year was selected.

The most favorable location for recharge wells would also have to be high on the alluvial fan where the aquifers are relatively thick and coarse-grained. A value of 2500 gallons per minute per well was selected as a reasonable estimate, with the wells spaced one to a quarter section. In eastern Utah, HSU 7, 8, and 9, where the only large aquifers are in bedrock, artificial recharge is not practicable.

Based on the cited criteria, limits on the amount of water that can be artificially recharged each year in each HSU were determined; these are given in Table 4. In practically all cases the fans are at present full or nearly full of water, and a program of artificial recharge would depend upon lowering of the water table in the fans so that additional recharge could be accommodated.

Present water resource development availabilities are listed in the appendix.

Table 4. Limits on annual artificial recharge to ground-water basins.

Hydrologic Study Unit	Maximum Mean Annual Artificial Groundwater Recharge (ac-ft/yr)
1	0
2	60,000
3	366,000
4 (low cost)	434,000
4 (high cost)	100,000
5 (low cost)	52,000
5 (high cost)	52,000
6	65,000
7	0
8	0
9	0
10	0

THE MODEL

The model uses supply and demand analysis to determine efficient allocations. Since both supply of and demand for water are complex and numerous variables enter into these relationships, mathematical programming was chosen as the analytical technique.[3] This technique can be used to generate optimum values for the variables as well as shadow prices (equivalent to La Grange multipliers) which represent marginal cost or value of those variables. The technique does have some disadvantages, however. Non-linear relationships are costly and difficult to model, dynamic changes often must be simulated using only a few of the relevant variables, and stochastic (probabalistic) or uncertainty parameters are difficult to include. Thus, the use of the mathematical programming technique establishes constraints or limits within which the analytical model must be constructed and the results interpreted.

Description of the Allocation Model

The allocation model was established to maximize net profits to agriculture for the entire state, given municipal, industrial, and wetland requirements. by maximizing the difference between returns to agriculture (net of non-water-related costs of production) and costs of water use for agricultural production. Figure 2 is a schematic representation of the allocation model. Note that while the cost of providing municipal and industrial (M&I) and wetlands with water is included, efficient allocation is dependent upon the agricultural sector. Maximizing net returns is equivalent to equating supply (marginal cost) with demand (value of the marginal product), so that the solutions are in fact the economically efficient allocations. (See Keith et al., 1973, for elaboration of efficiency criteria in the model.)

Coefficients in the constraint matrix fell into three categories: (1) Technical relationships of development of water sources and distribution systems; (2) productivity relationships between inputs and outputs in agriculture, including rotation requirements; and (3) water, land, labor, and other input availabilities. Prices of outputs and costs of inputs were included in the objective function. Maximum and/or minimum bounds were established for each variable, as appropriate, and limits on each constraint (termed right-hand-side values) were determined. (A full listing of all variables, constraints, bounds, limits, and coefficients may be found in Keith et al. (1973).)

Variables included in the supply part of the model were water sources, amounts or availability from those sources, losses and requirements for various transportation and distribution systems, various outflows from both HSU and the state, and reuse capabilities. The costs of delivery (except on farm distribution systems), treatment, and other reuse technology, were included in the objective function on a per acre-foot basis.

Variables included in the agricultural demand part of the model were productivities, input requirements, and rotation constraints for each crop, land class, and county (or part of county) in each HSU. Costs of inputs (other than water), including new land development and on-farm distribution costs, and prices of outputs were part of the objective function. Production or demand variables were on a per-acre basis. Within the linkages between agricultural supply and demand, a factor relating acres of production to acre-feet of water use was necessary to make the two model parts compatible.

A simple explanation of the model's functioning is as follows:

(1) M&I and wetland requirements were met from available sources, leaving the residual water for agriculture.

(2) The costs of water from various sources were compared to the value produced by the water for various crops in the possible rotation patterns.

(3) Water was allocated to agriculture from alternative sources in the iterative process of the programming algorithm until further application was not profitable (either because the available land had less productivity than would warrant application of water, or

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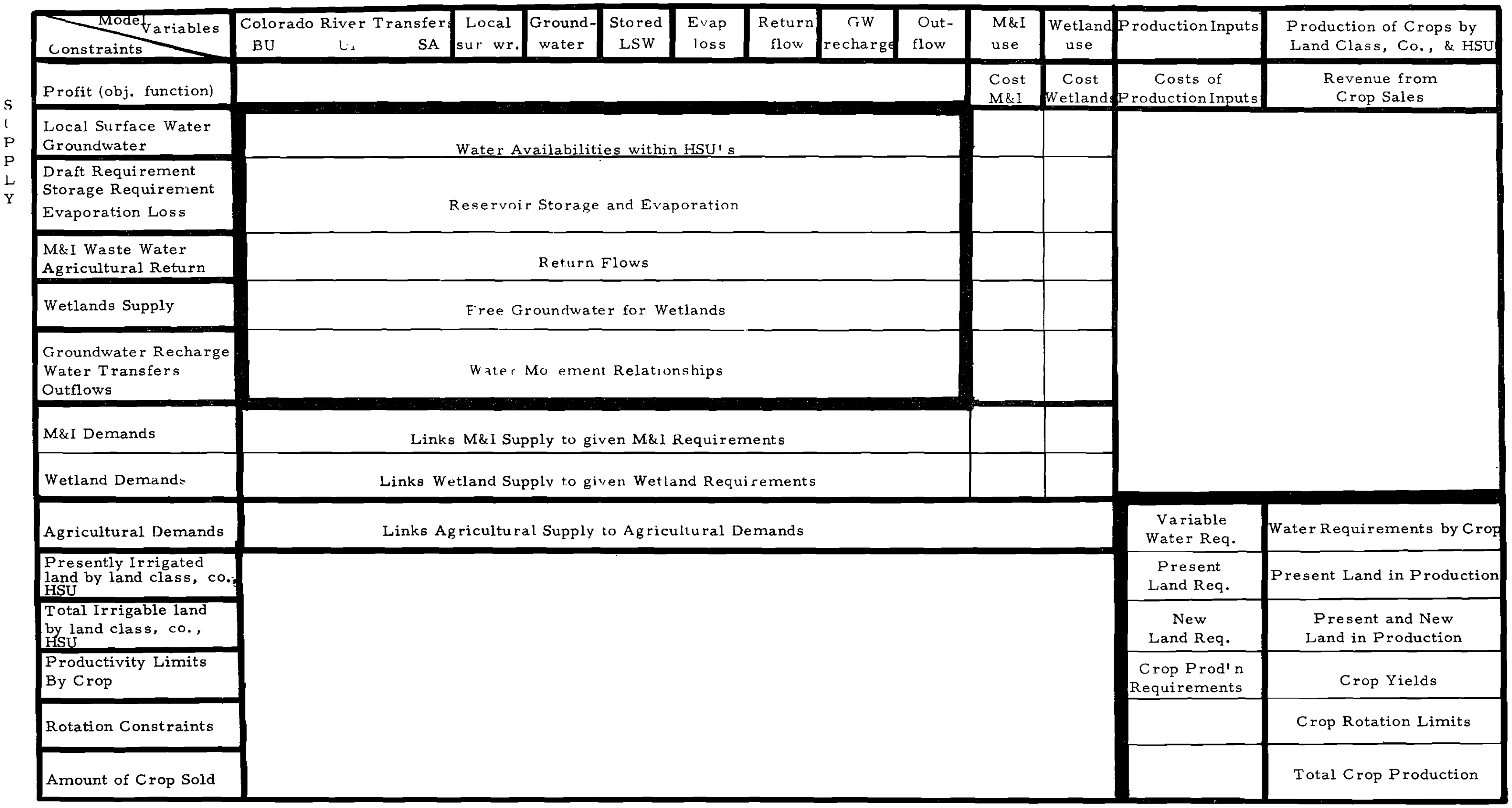
[3] This technique has been applied to other models of water resource allocations (Gisser, 1970; Hall et al., 1967; Howes, 1966). The general statement of the mathematical program is (Hadley, 1962):

Maximize (Minimize)

$$Z = CX$$
$$AX \gtreqless B$$

Subject to AX

where Z is the value of the objective function.
C is a (1xN) vector of returns (costs), c_i
X is an (Nx1) vector of variables, x_i
B is an (Mx1) vector or righthand side value, b_j
A is an (MxN) matrix of coefficients, a_{ij} of the N variables in M equations ($N \geq M$).



SUPPLY

Constraints \ Model Variables	Colorado River Transfers BU [illegible] SA	Local sur wr.	Ground-water	Stored LSW	Evap loss	Return flow	GW recharge	Out-flow	M&I use	Wetland use	Production Inputs	Production of Crops by Land Class, Co., & HSU
Profit (obj. function)									Cost M&I	Cost Wetlands	Costs of Production Inputs	Revenue from Crop Sales
Local Surface Water Groundwater	Water Availabilities within HSU's											
Draft Requirement Storage Requirement Evaporation Loss	Reservoir Storage and Evaporation											
M&I Waste Water Agricultural Return	Return Flows											
Wetlands Supply	Free Groundwater for Wetlands											
Groundwater Recharge Water Transfers Outflows	Water Movement Relationships											
M&I Demands	Links M&I Supply to given M&I Requirements											
Wetland Demands	Links Wetland Supply to given Wetland Requirements											
Agricultural Demands	Links Agricultural Supply to Agricultural Demands										Variable Water Req.	Water Requirements by Crop
Presently Irrigated land by land class, co., HSU											Present Land Req.	Present Land in Production
Total Irrigable land by land class, co., HSU											New Land Req.	Present and New Land in Production
Productivity Limits By Crop											Crop Prod'n Requirements	Crop Yields
Rotation Constraints												Crop Rotation Limits
Amount of Crop Sold												Total Crop Production

DEMAND

Figure 2. Diagrammatic representation of the programming model.

because the sources of water which could be provided at sufficiently low cost to yield profits were exhausted).

The model's output included each crop's production (total and by land class, county, and HSU), total profit, agricultural water used by source, sources of water used by M&I and wetlands. Shadow prices for each variable allowed construction of both supply and demand curves (see Anderson et al., 1973). Solutions were generated for changed conditions and projected futures by altering coefficients and requirements appropriately. The applicability of these solutions is determined by the accuracy of the data and coefficients used in the supply and demand portions of the model.

Supply Coefficients

The components of water cost were those costs associated with a particular function or process which when summed give the total cost associated with a particular allocation. These costs were the cost coefficients which appeared in the objective function of the linear programming problem. As the sources change from lowest to highest cost (as the programming algorithm used them), an upward sloping, "stepped" function is determined, which will approximate a normal supply curve.[4]

Components of water cost

Water transfer.

Water transfers under consideration here were of three types: (1) New facilities to move Colorado River water to the Great Basin, (2) present facilities which move water from one basin to another, and (3) new facilities for other interbasin transfers.

Colorado River water to surface water pool. The components were related primarily to elements of the Central Utah Project with a small amount of additional water delivered from the Uintah Basin to the Sevier River and identified in the model as Sevier Area (SA). Joint costs which occur when a project element contributes to the production of more than one output have not been precisely allocated in the planning; the costs shown in columns 2, 3. and 4, of Table 6 are conservative estimates of the costs of supplying agricultural water alone, netting out costs of power production, recreation, etc. They were based on generalized investigations of volume of water moved and distance covered. Note that these costs are not complete for moving and using water. Storage and collection costs at the point of origin of water as well as distribution and possible treatment costs (at the point of use) were added in the complete model. A single type of facility was assumed for moving water for whatever its final use might be. Differences in distribution costs or treatment were considered separately. The transferred water was assumed to be released into the surface water pool of the HSU indicated in column 1 and to become part of the available surface water.

Present diversions. Facilities have already been constructed to transfer some water from one basin to another. In some cases these transfers are distributed directly to agriculture. Column 5 indicates the HSU receiving the water from the HSU listed in column 1 and column 6 shows the cost. This cost was only that for operating and maintenance (O&M) since capital costs are considered as sunk costs and were not part of the optimization problem. Other facilities have been constructed to transfer water directly to municipal and industrial (M&I) use. Column 7 indicates the HSU receiving the water and column 8 the O&M cost. Additionally, facilities have already been constructed to transfer water from one HSU and release it in the surface water pool of another HSU. Column 9 indicates the HSU receiving the water and column 10 shows the associated O&M cost.

New diversions to surface water pool. New facilities which might be constructed to move water from one HSU to another were considered in the allocation problem. Column 11 indicates the HSU that feasibly could receive water from the HSU listed in column 1. Column 12 shows the total cost of building and operating the facilities for making the indicated transfers. Capital costs as well as O&M costs were included.

Storage

Present storage. Costs shown in column 13 represent the O&M costs only since capital costs associated with already constructed facilities are not part of the optimization problem.

New storage. Costs of new storage facilities shown in column 14 were based primarily on the estimates of size and quality of remaining reservoir sites. Storage at sites near collection points and sites nearer the point of use were included. The cost includes capital costs as well as O&M costs.

Agricultural distribution

These costs are for the diversion works and distribution facilities. Distribution costs for present diversions include only O&M whereas for new diversions the cost includes capital costs as well. Cost of storage facilities or on-farm ditches was not included. The on-farm costs were more logically determined as a function of acreage than acre-feet of water diverted, and therefore were included in the agricultural demand.

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[4] Note that for a given source of water, costs are assumed to remain constant over the range of availability from that source.

Table 6. Cost components for supplying water in Utah. (Annual cost in dollars per acre-feet).

Hydrologic Study Unit	Transfer Costs[c]											Storage costs	
	Colorado River water to surface water pool[a]			Present diversions direct to agriculture		Present diversions direct to M&I		Present diversions to surface water pool		New diversions to surface water pool		Present storage	New storage[f]
Column No.	Bonneville Unit, CUP	Ute Indian Unit CUP	Sevier area	To HSU	Cost (O&M)	To HSU	Cost (O&M)	To HSU	Cost (O&M)	To HSU	Cost	(O&M)	
1	2	3	4	5	6	7	8	[illegible]	10	[illegible]	12	13	14
Symbol[h] (X)[i]	CTBX	CTUX	CTSX	(Y)[j]	CTXAY	(Y)[j]	CTXMY	(Y)	CTPXSY	(Y)	CTNXSY	CPSX	CNSX
1						4	00					10	11.00
2										1&	4.00	[illegible]	4.70
3		10.00		2	1.00			4	.40	4	4.00	10	16.30
4	7.00	10.00	8.00							5	5.00	.10	13.00
5	10.00	13.00	4.00	9	1.00					6	4.00	.10	8.60
6												.10	14.00
7								4	40			10	10.80
8				5	1.00							10	7.20
9												10	13.50
10								6	40	6	4.00	10	14.30

Hydrologic Study Unit	Agricultural distribution costs				M&I distribution costs				M&I supply treatment costs[c]				Wastewater treatment costs[d]		Recharge groundwater basin costs[g]		
	Present diversions (O&M)		New diversions[b]		Present diversions (O&M)		New diversions[h]		Present diversions (O&M)		New diversions		Return to Local surface water	Return to Ground water	Recharge	Collection system to local surface water	Transport to distant points
Column No	Local surface water	Ground-water	Local surface water	Ground-water	Local surface water	Ground water	Local surface water	Ground water	Local surface water	Ground water	Local surface water	Ground water					
1	15	16	17	18	19	20	21	22	[illegible]	24	25	26	27	[illegible]	[illegible]	30	31
Symbol[h] (X)[i]	CADPSX	CADPGX	CADNSX	CADNGX	CMDPSX	CMDNSX	CMDPGX	CMDNGX	CMTPSX	CMTPGX	CMTNSX	CMTNGX	CWTSX	CWTGX	CRCX	CCSX	CTRCX
1	.75	1.25	5.25	1.50	16.00	23.80	42.00	42.00	1.00	20	5.00	25	26.00	4.00	15.00	00	
2	.75	1.75	4.75	2.00	16.00	23.80	42.00	42.00	1.00	20	5.00	.25	26.00	14.00	15.00	2.00	
3	75	2.00	5.50	2.25	16.00	29.50	42.00	49.00	4.00	50	17.00	65	26.00	14.00	15.00	2.00	
4	.75	2.75	5.25	3.00	16.00	29.50	42.00	49.00	4.00	.50	17.00	65	26.00	14.00	15.00	2.00	6.00
5	75	1.75	4.75	2.00	16.00	23.80	42.00	42.00	2.00	20	10.00	25	[illegible]	14.00	15.00	2.00	6.00
6	.75	2.25	4.50	2.50	16.00	23.80	42.00	42.00	2.00	20	10.00	25	26.00	14.00	15.00	2.00	
7	75	1.00	5.25	1.25	16.00	23.80	42.00	42.00	2.00	20	10.00	25	26.00	14.00	15.00	2.00	
8	.75	-	5.25	-	16.00		42.00	-	6.00		25.00		26.00				
9	75		5.25		16.00		42.00		4.00		17.00		26.00				
10	75	1.25	5.25	1.50	16.00	23.80	42.00	42.00	4.00	20	17.00	25	26.00	14.00	15.00	2.00	

[a] These values are only rough approximations. These costs are not strictly separable in the available data on this project. These costs do not include the storage at collection.

[b] These costs pertain to newly developed water supplies. They do not include storage costs.

[c] Treatment costs for surface water vary according to the amount of filtration and other measures required. Treatment of groundwater is only chlorination.

[d] Primary and secondary treatment is required for returning water to surface flows. Primary treatment only is required for returning to groundwater.

[e] Water transfer costs are based on average cost data for transporting water which depends on amount of water moved and the distance.

[f] Based on size and quality estimates of available reservoir sites.

[g] The recharging cost is for spreading ponds and pits for getting water into ground. The collection system is for bringing the water from various places to the point of recharge, except in areas 4 and 5 a portion of the water which could be recharged is at inconvenient and expensive places to recover. Hence the $6 charge applies to part of the water for extra transport and collection costs.

[h] This represents the symbol used in the summation of cost components for the cost coefficients of the variables in the objective function.

[i] The X represents the general form of the cost component as it appears in the cost coefficient summation equation and is for the HSU numbered below

[j] The Y represents the general form of the cost component as it appears in the cost coefficient summation equation and is for the HSU receiving water

Sources of the Data in Table 9

Christensen, Max L. 1961. Cost of pumping irrigation water in Central Utah. U.S. Bureau of Reclamation, Salt Lake City Utah. 22 p.

Davis, Lynn H. and Duane R. Price. 1967. Economics of crop production and irrigation water pumping, Milford Area, Utah. Utah Resources Series 38, Agr. Exp. Sta., Utah State University Logan, Utah. 24 p.

Frankel, Richard J. 1967. Economics of artificial recharge for municipal water supply. Symposium of Haifa, Publication No. 72, Association Internationale d'Hydrologie Scientifique, Gentbrugge, Belgium (RRF Reprint No. 62). 13 p

Kirchhoff, Bruce 1969 An inventory of municipal water and waste water systems in 54 Utah cities Western Interstate Commission for Higher Education (Economic Development Internship Program) 136 p

Löf, George O. G. and Clayton H. Hardison 1966 Storage requirements for water in the United States Water Resources Research 2(3):323-354

Moore, Charles V. and Trimble R. Hedges 1962 Some characteristics of farm irrigation water supplies in the San Joaquin Valley Giannini Foundation Research Report No. 258 California Agr. Exp. Sta. University of California 42 p

Nelson, Aaron G. and Charles G. Busch 1967 Cost of pumping irrigation water in central Arizona Technical Bulletin 182 Arizona Agr. Exp. Sta. University of Arizona Tucson Arizona. 44 p

Nelson, W. B. 1954. "Pumping costs in southwestern Utah" in Progress report on selected groundwater basins in Utah State Engineer's Office Technical Publication No. 9. Salt Lake City Utah p. 95-104

Parkhurst, John D. and Walter F. Garrison 1964 Whittier Narrows water reclamation plant. Civil Engineering 34(9):60-63

Smith, Robert 1968 Cost of conventional and advanced treatment of wastewater Journal of the Water Pollution Control Federation 40(9) 1546 1574

Todd, David K. 1965 Economics of groundwater recharge ASCE Journal of Hydraulics Division 91(HY4) 249 270

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Cottonwood Creek Consolidated Irrigation Co. 1969
Muddy Creek Irrigation Co., 1969
Ferron Canal and Reservoir Co., 1969
Huntington-Cleveland Irrigation Co., 1969
Division of Water Resources, Department of Natural Resources, State of Utah, 1969
Utah Power and Light Co., 1969
Salt Lake County Water Conservancy District, 1969
Weber Basin Water Conservancy District, 1969
Price Municipal Corporation, 1969
Department of Water Supply and Waterworks, Salt Lake City, 1969
Metropolitan Water District Salt Lake City 1969

It was recognized that each water system will have a unique cost structure, but the data given in Table 6 represent averages for the size, terrain, and other factors that affect each HSU.

Present diversions. Columns 15 and 16 show the costs of distributing water to agriculture using facilities already constructed. These costs are only O&M since capital costs were not included in the optimization model. Column 15 is for diversions from local surface water while column 16 is from groundwater. The costs for groundwater included the power cost of pumping. Cost differences for each HSU reflect the depth from which water must be pumped.

New diversions. Costs shown in columns 17 and 18 represent the total cost of constructing and maintaining new facilities. These costs include capital costs as well as O&M costs.

Municipal and industrial distribution

Present diversions. Columns 19 and 20 show the costs associated with distributing water for municipal and industrial use using facilities already constructed. O&M costs only are included. Diversions from local surface water are shown in column 19 whereas diversions from groundwater are shown in column 20. The costs for groundwater diversion included the cost of pumping and the cost required to boost to line pressure. The pumping for municipal and industrial supplies has historically been more expensive than the pumping for irrigation for many reasons. The cost to boost to line pressure is essentially the same as for pumping to a higher elevation such as to storage tanks.

New diversions. Costs shown in columns 21 and 22 represent the total cost of constructing and maintaining new facilities. Capital costs are included with the O&M costs. Cost of pumping and boosting to line pressure is included in the groundwater costs.

Municipal and industrial supply treatment

Present diversions. Columns 23 and 24 show the costs of treating water using presently constructed facilities. Treatment costs for surface water shown in column 23 vary according to the amount of filtration and other measures needed to bring the water to acceptable standards. The values given represent averages. The only treatment for groundwater is chlorination, and only O&M costs are included.

New diversions. Costs shown in columns 25 and 26 reflect treatment costs associated with construction of new facilities. Capital costs as well as O&M costs are included.

Waste water reclamation

Another element of treatment costs considered was the process of reclaiming waste water from municipal and industrial uses for recycling in the system. Recycling can be accomplished by (1) Treating the waste water and returning it to the surface water pool where it is diluted, mixed, and eventually diverted into another M&I water supply system; (2) treating the waste water and returning it (by artificial recharge) to groundwater pool where it is diluted and, to an extent, purified and eventually pumped into another M&I water supply system; and (3) direct recycling by treating the waste water and returning it directly to the M&I water supply system. This third procedure was not considered in this study due to possible public aversion. Primary and secondary treatment was required for returning water to the surface water pool and is reflected in the costs shown in column 27. Primary treatment only was required for the return to groundwater as reflected in the lower costs shown in column 28.

Recharging groundwater basin

The recharging cost shown in column 29 is for land acquisition, construction, and operation of spreading ponds and pits for getting water into the ground. The collection system, column 30, is for bringing the local surface water from various places to the point where recharge is to be made. In subareas 4 and 5, it has been determined that a part of the water which could be recharged is at inconvenient and expensive places to recover. Hence, the $6.00 charge in column 31 applies to part of the water for extra transport and collection costs. Note that in this case, too, recharge was only one of the components. Treatment costs as well as pumping and distribution costs would be incurred in order to use this water supply source.

Construction of supply schedules

The supply model was developed as discussed, and supply schedules were derived in King et al. (1972). Figure 3 is an example of a supply schedule for agricultural water developed by King et al. (1972). This schedule illustrates the shadow price of agricultural water for alternative levels of M&I diversions. For any constant level of M&I diversion, the remainder of total water available can be used for agriculture, with each source costing a given amount per acre-foot. For example, at 1965 M&I diversions (approximately 300,000 acre-feet per year), about 725,000 acre-feet are available from presently developed local surface water at $.75 per acre-foot; 75,000 additional acre-feet are available from presently developed local groundwater at $2.75 per acre-foot; 50,000 additional acre-feet are available from new developments of surface water at $5.19 per acre-foot; 200,000 acre-feet are available from groundwater recharge at $5.75 per acre-foot. As M&I diversions increase, water is available to agriculture only from higher cost source (for example, from $112.52 acre-foot transfers when M&I

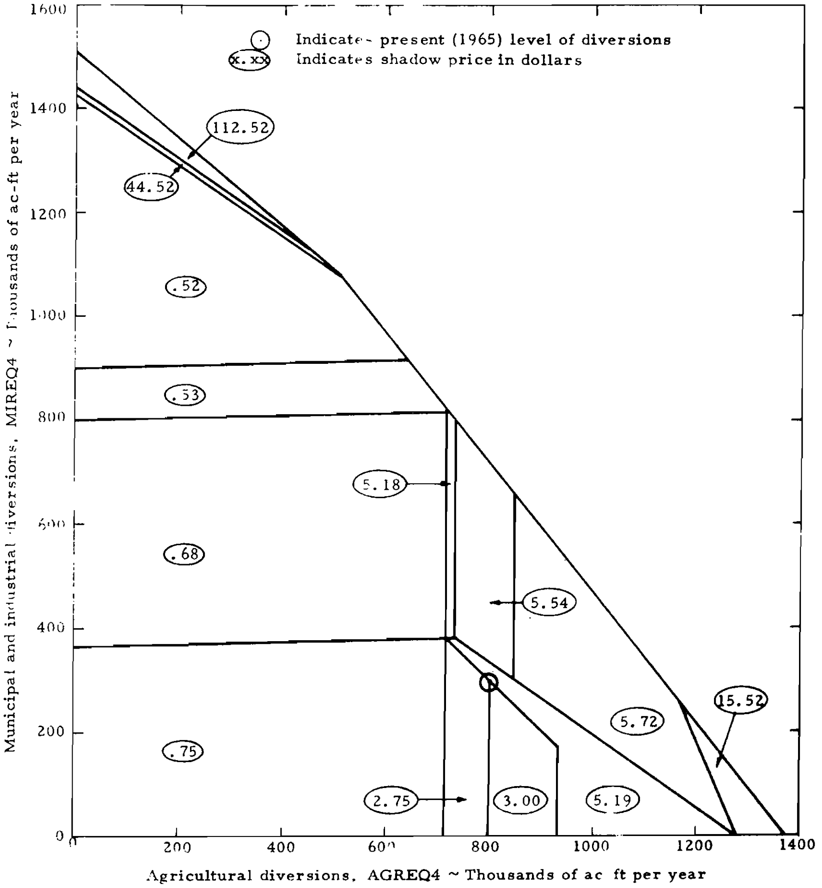

Figure 3. Supply function mapping for HSU 4.

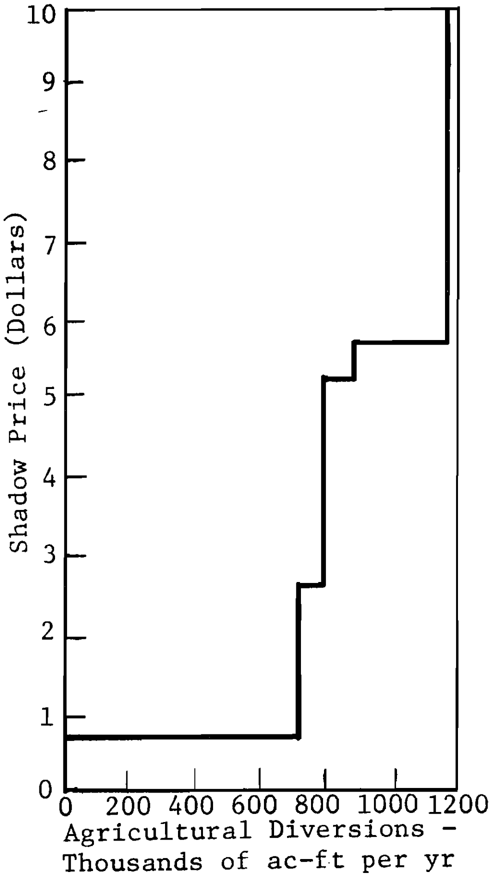

Figure 4. Supply curve for HSU 4 for M&I and wetland diversions for 1965.

diversions exceed 1,450,000 acre-feet/year). Figure 4 is the supply curve derived from 1965 M&I allocations as above (from Anderson, 1973). As M&I diversions increase, this supply function will shift upward.

With the completion of the supply side of the allocation problem, the next step was to determine the demand for water and include that demand in the programming model.

Demand and Demand Coefficients

Assumptions of demand analysis

Demand for water has been separated in M&I, wetland, and agricultural sectors. The development of a workable model specific to Utah required several assumptions, including:

(1) Municipal, industrial diversion requirements are fixed;
(2) Agricultural productivity is fixed at 1980 projections for an average manager;
(3) Agricultural prices will rise at the same relative rates as input costs; and
(4) Timing of water delivery is irrelevant to water value.

Municipal and industrial demands

The information on value of water in municipal and industrial uses is sketchy for highly aggregated sectors on a nationwide scale; for Utah, it is practically nonexistent. Therefore, municipal and industrial uses entered the model as alternative fixed diversions as projected for given years to 2020. The fixity of M&I diversions is equivalent to a perfectly inelastic demand curve for M&I water. The total demand curve retains the slope of the sum of the remaining demand curves, but is rightward of it by the amount of the M&I requirements. (The effect may also be viewed as a shift in the vertical axis of a demand model rightward to the quantity of water demanded by M&I users.)

Wetland consumption

The value of water for production of recreation, including provision for habitats for various wildlife and other wetland uses, is also not readily obtainable or available. Therefore, wetland consumption entered the model at fixed alternative levels or as a perfectly inelastic demand curve. The effect was to shift the total demand curve (or alternatively, the vertical axis) further rightward.

demands has little empirical foundation, although some evidence exists indicating household demands for water are relatively inelastic (Howe and Linaweaver, 1967). Alternative levels of wetland and M&I diversions were used to test the effect of wetland consumption on the model's solution and to simulate alternative present and future requirements. Any increase in these diversions shifted total demand rightward; decreases shifted the total demand curve in the opposite direction.

Agricultural productivity projections

As a result of assumptions of given M&I and wetland demands, only the value of the marginal product in the agricultural sector in each HSU determined efficient allocations within and between sectors and HSU's in the model. The productivity of agricultural water is dependent upon relationships with other factors of production, such as land quality, cropping patterns, and frost-free growing season. The model used per acre crop yields by land class by county within a given HSU as the appropriate production measure. Managerial ability, technological change, available input substitutes, and market conditions determine profitability for any given farm, so that further simplifying assumptions were necessary in order to obtain a workable model. An average farm manager as projected for 1980 was assumed. This implies:

a. Yields on a given class of land of a given crop in a given HSU were the HSU average for that class of land as projected for 1980.
b. Inputs per unit of a given crop production were the average for the given HSU and land class, including labor, water, and other variables, and were utilized in fixed proportions as projected for 1980. Variable and fixed input costs were identified, the former with amounts of crops grown, the latter with acreages of land in production. Both present and potential land developments were identified by class, county, and HSU.
c. Rotations of crops were the normal rotations for the HSU.

As a result, unit profitability and, therefore, the VMP was constant for each crop on a given land class in a given county within a given HSU. Thus, each county had a stepped VMP curve including segments for crop rotation pattern by land class. Since increasing agricultural production involves less and less productive land classes, these stepped VMP curves were downward sloping.[5] The HSU curve was the sum of the county curves and was also stepped and downward sloping. Since there were seven possible crops on five land classes for each county, a sufficient number of "steps" to provide an approximation of a continuous VMP curve were included.

Agricultural productivity has shown increases in the past, and could well increase beyond 1980 as a result of technological and cultural improvements (Anderson, 1972). On the other hand, there is some reason to believe that some productivity may fall as a result of restricted cultural practices required by environmental quality limitations. The model over- or underestimated the value of transfers, depending upon the effect of these and other factors not explicitly included in the analysis.

Agricultural prices

Prices of agricultural products and costs of production inputs were assumed to change at the same relative rate, so that profitability of each crop on each land class in each county remained constant over time, given the productivity levels.[6]

Trends over time would indicate that agricultural product prices rise at a considerably slower rate than do costs of production (Tweeten, 1970). However, technological advancement in production has previously offset the relative increase in input prices. The model under- or overestimated agricultural profitability, depending upon the relative changes in input prices and technological advancement. The VMP curves in agriculture were assumed to be subject to aggregation between HSU's, which implies that average agricultural income and all other prices are constant and equal as among all HSU's.

Timing of delivery

In the study, timing of water delivery was assumed irrelevant to its value. Often in arid regions, late season water is considerably more productive and, therefore, more valuable than early season water at the margin (Hiskey, 1972). However, the productivity of water in the model was an "average" marginal productivity over the growing season so that the model overestimated or underestimated the value of water transfers, depending upon the relative differences between each season's water and the model's "average."

Development of new land

Any new land developed was assumed to contain the same proportions of land classes (with the exception of the least productive land classes) as presently developed land. All land surrounding present water delivery systems was assumed to have been developed. Newly-developed land incurred costs commensurate with the development and delivery of new water. Presently-developed water could not be applied to new lands at the present cost. Presently-developed land could, however, use newly-developed water at costs net of new delivery costs.

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[5] Diminishing marginal returns to water on a given land class were assumed away; diminishing returns might be expected to produce a continuous downward sloping demand curve.

[6] G. Edward Schuh (1973), in an unpublished paper, indicates that there may have been a significant change in the structural relationships in the agricultural sector.

Demand coefficients

Municipal and industrial requirements

The determinations of M&I requirements for a given time period were based jointly on population projections and the projected development of industry in each HSU.

Population and water use projections for the model for all HSU's except 7, 8, and 9, were taken from: (1) The Framework Studies (Pacific Southwest Inter-Agency Committee [PSIAC], 1971a, 1971d, 1971e, and 1971h); (2) the Office of Business Economics, Department of Commerce, and the Economic Research Service, Department of Agriculture, projections [U.S. Water Resources Council, 1969 (commonly known as the OBERS projections)]; (3) 1970 Utah Division of Water Resource projections (1970); (4) 1972 revisions of the three sets of projections; and (5) a median of all these.

Some of these projections differ from the median projection considerably. The 1972 revision of the OBERS projection utilizes a much-reduced population growth rate, about .5 percent per annum, as indicated for the national mean growth rate in recent census data. This projection falls about 20-30 percent below the median projections. The 1970 Division of Water Resources projections included a rapid increase in industrial development for the state and is consistently 15-20 percent above the median projection. The other three projections are reasonably close to the median. Table 7 contains various projections of population and diversions. The median projections were used in this model.

Projections of growth and water use for HSU 7, 8, and 9, were complicated by potential large developments of the extractive oil shale industry and construction of high-output fossil-fueled power generation plants.[7] The oil shale industry will be confined primarily to HSU 7, the Uintah Basin. The Comprehensive Framework Study, which relies heavily on the OBERS projections, did not include impacts of the oil shale industry (Pacific Southwest Inter-Agency Committee, 1971e), while the Division of Water Resources (1970, 1972) includes only a small development. Water use was calculated from data for the industry and from requirement coefficients for supporting municipal and industrial facilities, including once-through use and no in-place extraction (U.S. Bureau of Mines, 1958; U.S. Senate Hearings, 1965; U.S. Senate Hearing, 1970; and U.S. Senate Hearings, 1972). (See Table 8.)

Slow, moderate and rapid rates of development of the oil shale industry were considered. The recent past indicates oil shale may not be developed until other sources from which petroleum can be obtained with less ecological disturbance are exhausted. A slow rate of development, wherein full production of one million barrels of oil a day would not be attained until after 2020, is most probable. A moderate rate of development from which about 1½ million barrels a day would be produced by 2000 was assumed. The indicated median projections which were used in the model include this moderate rate of development.

Fossil fuel power generation plants are presently under construction (State Engineer, 1964) and in partial production in HSU 8 and 9. Even though further expansion may be severely slowed by environmental considerations, the study assumed a moderate development rate of full power generation capabilities and alternative projections of population increases. Tables 9 and 10 indicate the range of water diversions for HSU 8 and HSU 9 respectively. The diversions of 98,800 acre-feet/year would provide for the generation of about 5,000 megawatts in Utah. These diversions are about 15,000 acre-feet below the projected requirements (Pacific Southwest Inter-Agency Committee, 1971i). Potential technological improvements in water use by steam generation facilities before 2020 should allow production of the full 5,800 megawatts using the model's diversions (Federal Power Commission, 1971).

Wetland requirements

Wetland requirements were the inflows necessary to maintain the current water levels in the various wetlands, such as marshes and lakes. These requirements are equal to the present evaporation of water plus the evapotranspiration by phreatophytes and other plants.

Some water salvage was permitted in the model in which wetland inflows were the sources of salvageable water. The wetland reuirement in a given HSU in the model was lowered to "release" water for upstream use (the wetland and total demand curves shift leftward for that HSU). Water salvage in the model did not include desalinization or other recycling processes. It was water which can be depleted from wetlands at no additional cost without seriously affecting the recreation on or aesthetics of those wetlands.

Only the maximum level of water salvage was examined. The data for potential salvageable water in each HSU used were based upon interviews and unpublished data from the Utah Division of Water Resources. Maximum salvageable water by HSU is listed in Table 11.

Inflows to the Great Salt Lake, while similar in nature to wetland requirements, were treated separately since these inflows are of a large magnitude and play a critical role in water use along the Wasatch Front. Alternative inflows to the Great Salt Lake included in the analysis were 1,014,000 acre-feet/year, the normal year inflow; 850,000 cre-feet/year; and 500,000 acre-feet/year.

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[7] Recently, large oil refining plants have been contemplated in the Uintah Basin, but these plants are not included in the projections.

Table 7. Projected population and water diversions.

HSU		1965	1980			2000			2020		
			M	H	L	M	H	L	M	H	L
1	Population	22,000	26.3	26.3	26.0	36.7	36.7	35.5	53.0	53.0	50.3
	Diversions	10 000	18.75	18.75	18.67	30.75	30.75	29.75	51.73	51.73	49.09
2	Population	70,000	83.5	88.3	83.5	112.0	132.9	112.0	146.8	197.0	146.8
	Diversions	44,000	72.31	76.47	72.31	109.98	130.51	109.98	149.00	199.96	149.10
3	Population	215,000	293.5	293.5	290.1	435.7	435.7	420.5	631.4	631.4	596.6
	Diversions	50,000	112.2	112.2	110.82	213.93	213.93	206.46	346.64	346.64	327.53
4	Population	567,000	722.5	722.7	714.2	1052.6	1053.4	1017.0	1527.3	1528.9	1441.8
	Diversions	303,000	447 23	447.23	442.08	676.82	677.34	653.93	1004.96	1006.02	948.80
5	Population	33,000	32.9	34.9	32.9	36.2	43.0	36.2	41.4	55.5	41.4
	Diversions	17,000	18.85	20.20	18.85	18.90	22.45	18.90	20.03	26.86	20.03
6	Population	16,000	17.1	18.0	17.1	20.3	24.2	20.3	25.6	34.3	25.6
	Diversions	13,000	13.41	14.11	13.41	14.74	17.57	14.74	19.02	25.48	19.02
7	Population	20,000	22.1	23.3	22.1	32.0	38.0	32.0	50.5	69.5	50.5
	Diver. with oil shale		25.61	26.66	25.61	68.99	81.93	68.99	123.67	170.21	123.67
	Diver. without oil shale	10,000	24.11	25.16	24.11	56.19	69.73	56.19	103.27	149.80	103.27
8	Population	26,000	23.8	25.2	23.8	29.0	34.5	29.0	37.1	48.8	37.1
	Diversions	12,000	25.44	26.94	25.44	43.91	52.23	43.91	58.80	77.35	58.80
9	Population	16,000	18.0	18.9	18.0	19.9	23.7	19.9	24.8	38.6	24.8
	Diversions	7,000	60.93	63.98	60.93	93.33	111.15	93.33	124.37	174.90	124.37
10	Population	12,000	26.3	27.9	26.3	34.5	41.0	34.5	44.3	59.5	44.3
	Diversions	4,000	9.07	9.62	9.07	12.04	14.31	12.04	16.08	21.60	16.08

M - Medium
H - High
L - Low

Table 8. **Projected M&I diversions (x 1000), HSU 7.**

With and Without Moderate Oil Shale Development	1980	2000	2020
High Population with Oil	26.6	81.9	170.2
Low Population with Oil	25.6	69.0	123.7
High Population without Oil	25.2	69.1	149.8
Low Population without Oil	25.6	56.2	103.3

Table 9. **Projected M&I diversions (x 1000), HSU 8.**

With and Without Moderate Power Development	1980	2000	2020
High Population with Power	26.9	52.2	77.4
Low Population with Power (Median)	25.4	43.9	58.8
High Population without Power	12.5	37.8	63.0
Low Population without Power	11.0	29.5	44.8

Table 10. Projected M&I diversions (x 1000), HSU 9.

With and Without Power	1980	2000	2020
High Population with Power	64.0	111.2	174.9
Low Population with Power (Median)	60.9	93.3	124.4
High Population without Power	28.0	39.2	102.9
Low Population without Power	24.9	21.3	40.4

Parameterizations

The model was parameterized by using changes in the M&I requirement. A linear interpolation was used to calculate diversion requirements for years between the data source projection dates (1980, 2000, and 2020). Then parameterization of the model was accomplished by systematically altering the M&I requirements in each HSU to approximate the water needed by projected populations and growing industrial use for 1965, 1980, 1990, 2000, 2010, and 2020 Optimal solutions were generated for M&I requirements so that the changes in the efficient alternatives over time were examined. Such "temporal" parameterizations of M&I requirements were done for each of the three alternative inflows to the Great Salt Lake mentioned above and no water salvage, and for 850,000 acre-feet/year and 1,014,000 acre-feet/year inflows with salvage.[8] The solutions generated were compared to determine the effect of public policies on allocations of water.

Agricultural demand

The empirical problem of determining coefficients for agricultural productivity was a large one. The research effort was to determine and gather the most unbiased, scientifically sound. and most consistent information available. All information (yield, land acres, costs, etc.) was broken down on the basis of counties and parts of counties within each hydrologic subregion. All numbers in

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[8] For inflows less than 500,000 acre-feet/year with no salvage, and less than 850,000 acre-feet/year with salvage, no change in the solutions were observable.

Table 11. Salvageable water by HSU.

HSU	Salvageable Water (Acre Feet)
1	0
2	120,000
3	50,000
4	40,000
5	53,000
6	0
7	0
8	20,000
9	0
10	0

the demand portion of the model in each region are on a per acre basis.

The potentially irrigable and presently irrigated land class acreages are revised estimates based on information obtained primarily from PSIAC (1971b, 1971c, 1971f, 1971g), Pugh (1971), Shafer (1971). These data were altered so that they would more closely conform with information found by the Utah Conservation Needs Committee (1970) and by Wilson, Hutchings, and Shafer (1968). The raw figures were obtained from the PSIAC reports, Pugh (1971), and Shafer (1971) because they were the only available sources that listed land class acreages for each county in the state on both presently irrigated and potentially irrigable land. However, these acreages were not adjusted for climate; consequently, the climate variable was included to increase the accuracy of the model. The Utah Conservation Needs Committee (1970) report was consulted to help make the needed changes. The land class percentage breakdown, county by county, was calculated and applied to the presently irrigated PSIAC estimates and, in altered form, to the potentially irrigable acreages. Wilson, Hutchings, and Shafer (1968) were used in some areas to determine the amount of presently and potentially irrigable land in each region when a county was included in more than one hydrologic subregion. Climatic information from Richardson (1971) was also used in preparing the data. Wilson (1972) and Shafer (1972) made revisions based on information from their offices.

"Greenbelt studies" (Davis, Christensen, and Richards, 1972), information from the U.S. Department of Commerce (1964, 1969), and consultation with personnel from the Utah State University Plant Science Department and Extension Services were used to determine the crops considered in the model and the rotation constraints to be applied to these crops. The crops which were included in this study are barley, corn silage, sugar beets, alfalfa hay, irrigated pasture, and dry-land wheat. Dry-land wheat was the only crop which can be grown alone; all other crops had to be grown in rotation. The basic rotation constraints are as follows:

1. Alfalfa Acreage   Barley Acreage
2. Barley Acreage   Nurse Crop Acreage
3. Alfalfa Acreage   5 (Nurse Crop Acreage)
4. Alfalfa + Barley + Nurse Acreage   7 (Sugar Beet Acreage)
5. Alfalfa + Barley + Nurse Acreage   7 (Corn Silage Acreage)

Alfalfa production was composed of two activities: alfalfa grown with a full or a partial supply of water. Alfalfa was limited to a maximum of 5 years in succession, except in Daggett County, where, because yields are low and much of the hay is really grass hay, 8 years were allowed. Then the crops had to be rotated with at least one but not more than 5 years of barley and a nurse crop (except in Daggett County, where there is no barley activity). Corn silage and sugar beets were limited to 1/7 of the irrigated acreage where they can be grown. If these crops were both grown in a county, they were each limited to 1/9 of the total acreage. These rotation constraints allowed numerous combinations of the crops (although only five of the combinations were economically feasible). Water shortage was met by one of three alternatives (or a combination of the three); (1) Reduce the amount of land under irrigation; (2) change to a crop rotation which is less intensive; (3) shift from producing alfalfa with a full supply of water to producing it with a partial supply (and a lower yield).

Corn and sugar beets were restricted from being grown in certain counties. Both of these crops are subject to crop failure due to late spring and early fall frost. This is particularly serious due to the heavy capital investment which is required (especially in sugar beet production). Sugar beet production is also restricted by heavy seasonal labor requirements and by the closing of all but one of the sugar refining plants in Utah. However, where they are successfully grown, these crops are very profitable. In the model, neither corn nor sugar beets could be grown on Class IV or less productive land. Sugar beets were restricted, by upper bounds, to approximately their present acreage. When new land was brought into production, sugar beets could be planted on it in the same percentage as on the presently irrigated land. In any county where sugar beet production was allowed, the acreage was controlled by either the upper bound or rotation constraint (whichever was lower). According to data in the Utah Census of Agriculture, sugar beet acreage has been decreasing over time while corn silage production has increased rapidly. Therefore, no limits (other than the rotation constraints) were placed on silage acreage. This allowed corn silage production to increase over present levels.

The nurse crop activity was used to bring alfalfa hay into production. Alfalfa is planted along with barley. The barley is harvested the first year (with a lower yield and higher costs), and alfalfa hay is then produced for the next 5 years (8 in Daggett County). Every county had a nurse crop activity. Barley was grown both as a nurse and as a cash crop in every county except Daggett. Irrigated pasture was allowed only on presently irrigated land which was classified as being poorer than Class IV, and pasture was the only crop which was cultivated on that land

Dry land wheat was restricted to potentially irrigable land in counties where significant amounts of it are already grown. Information from the U.S. Department of Commerce (1964, 1969) was used to determine the amount of non-irrigated land which is presently used for the production of hay, wheat, and barley. This value was used as the upper bound for the acreage in the dry land wheat activity in each county in the model. Wheat is grown every other year on a particular acre of land in an effort to conserve soil moisture. To approximate this situation in the model, all of the available land was planted each year but yields, cost, and other factors were reduced by one-half.

The agricultural cost and return information for this study was based on the "Greenbelt" budgets (Davis, Christensen, and Richards, 1972).[9] The Tax Commission requested that the Utah State University Economics Department determine an agricultural use value of privately owned land In compliance, USU staff members determined land rental values and sales price, the crop rotation schedule, costs of production, yields, etc., in each of Utah's 29 counties.

Projections of past trends (Daly and Egbert, 1966; Pacific Southwest Inter-Agency Committee, 1971a, 1971d; Economic Report of the President, 1968; and Christensen and Richards, 1969) were used to estimate production relationships and prices for the year 1980.

A revised Blaney-Criddle model was used (see U.S. Department of Agriculture, Soil Conservation Service, 1967, and Criddle, Harris, and Willardson, 1962), along with climatic information from Richardson (1972) and other sources) to determine the consumptive irrigation water use requirement for every crop in each county in each hydrologic subregion. Estimated supply from soil moisture storage and effective precipitation was subtracted from potential consumptive irrigation requirements for each crop. These consumptive use figures for each subregion were transformed into diversions by the model using irrigation system efficiency factors which have been developed for each region (see Clyde, King, and Andersen, 1971; and King et al., 1972). These efficiency factors accounted for groundwater recharge, evaporation while in transit, and other water losses.

Evidence indicates that the evapotranspiration-crop yield relationship is virtually linear over the relevant range for the crops used in this study (Stewart and Hagan, 1969). This implies that a single water level and yield for crops other than alfalfa could be used. Alfalfa required more than one water and yield level because of the possibility of raising a different number of crops (cuttings) during the growing season (Anderson, 1972). The revised Blaney-Criddle model was used to determine a "full" water supply level for all of the irrigated crops used in the study except alfalfa, which had two levels of yield and water use in each county.

The irrigation hours estimates were based on the crop involved and upon the irrigation consumptive use. It was estimated that the first watering on alfalfa, barley, nurse crop, and pasture would require 1 hour and that each subsequent irrigation would take 3/4 of an hour. It was assumed that the first irrigation on corn would require 1¼ hours and that each watering after that would take 1 hour. The first watering of sugar beets was estimated to require 2 hours; the next two waterings 1½ hours each, and each irrigation after the third, 1 hour. The consumptive use figures which were obtained from the revised Blaney-Criddle model were used to determine the number of irrigations for each crop in each county It was estimated that alfalfa, nurse crop, and corn would consumptively use .4 acre-feet of water per irrigation; that barley and pasture would require .3 acre-feet per watering; and that sugar beets would require .25 acre-feet. To determine the number of irrigations involved, the amount of water used per irrigation was divided into the consumptive use requirement for that crop in each area. Any

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[9] The "Greenbelt" figures were revised slightly for this study to make them more applicable to the water allocation problem The costs associated with the production activities were divided into average and variable components although the definitions of average and variable costs which follow are not the typical economic definitions but were used for convenience and to clarify the input information Average costs were viewed as being "fixed" once the decision was made to grow a certain crop. Average costs are those costs, such as fixed overhead, seed, and plowing, which must be met before production can occur. Variable costs were those costs which vary with the amount of output, the number of cuttings, or the number of irrigations Variable costs were assumed to be the same throughout the state, while average costs were slightly different due to differences in production activities. Information from the U.S. Department of Commerce (1964, 1969); Davis, Christensen, and Richards (1972), and PSIAC (1971a, pp. 128-131, 1971d, pp. 45, 129-132, and 137) was used to estimate these costs.

value that was .25 of an irrigation or greater was rounded up to the next irrigation. Labor was assumed to command a price of $2.00 per hour for irrigation, cultivation, and harvest.

Several sources were used to determine the costs of bringing each potentially irrigable land class into irrigated production. Included in these sources were Wilson (1969); U.S. Department of the Interior, Bureau of Reclamation (1957, 1961, 1964); Stewart (1960); PSIAC (1971c, 1971f); U.S. Department of Agriculture, (1958); and conversations with representatives of the Logan Soil Conservation Service office. Data from the U.S. Department of Commerce (1964, 1969) and information from the Economic Report of the President (1968), were used to modify these cost estimates. The development cost on a yearly basis was obtained by using an interest rate of 7 percent. It was estimated that the operation and maintenance cost (O&M) of existing water distribution networks would be $1.00 per acre on presently irrigated land. Additional O&M costs varied proportionally with the number of acre-feet used (see King et al., 1972).

Construction of the demand schedules

The demand model yielded demand curves as developed by Anderson (1972) and Anderson et al. (1973). The model structure is indicated in Figure 5, and corresponds to the demand portion of Figure 2.

Figure 6 is an example of a demand curve developed by parameterization of water availability. The water variables were incremented using this technique and at each change in productivity of the water (e.g., land class, rotation constraints or water source changes), shadow prices fell in accordance with the reduced profitability. Therefore, these shadow prices were equivalent to the marginal values of the product, and the trace of change is a "stepped" demand curve.

Once both the supply and demand portions of the model were completed the linking of the demand and supply models was accomplished using the agricultural water consumption–water diversion equations. Thus, solutions generated from the model indicated the economically efficient solution (demand equalled supply).

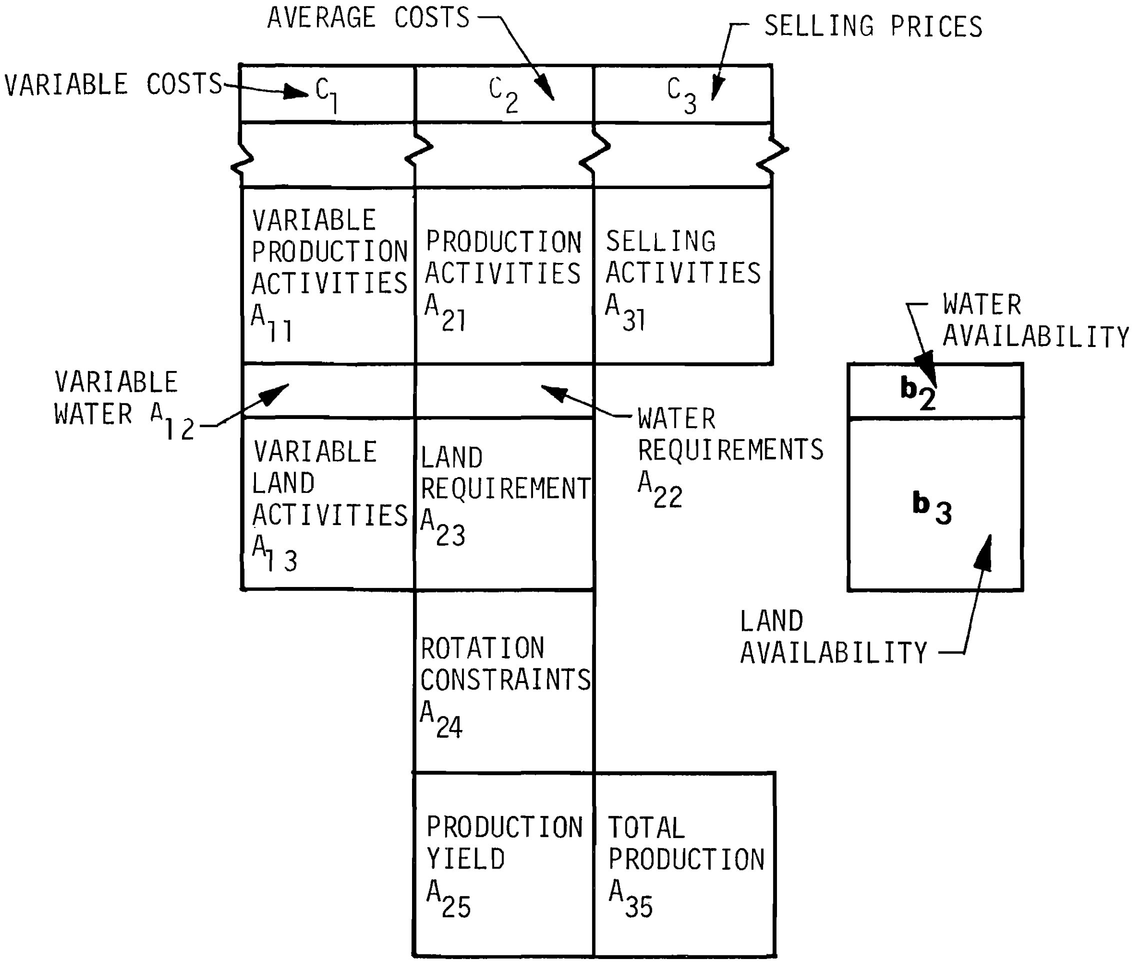

Figure 5. Diagrammatical representation of the programming model for agricultural demand.

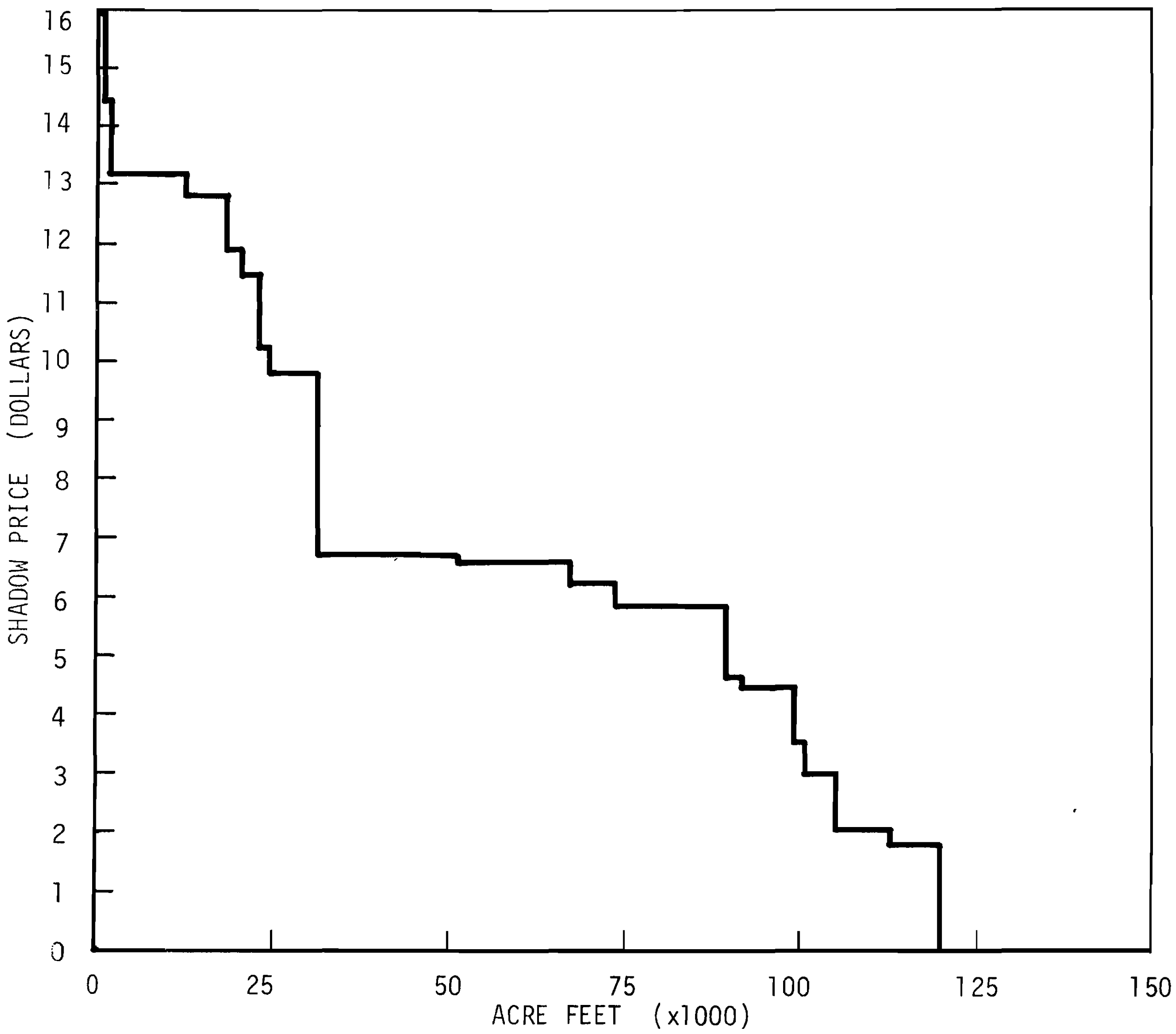

Figure 6. Demand for agricultural water in HSU 4.

ILLUSTRATIVE RESULTS FROM THE MODEL

Allocative Solutions

The allocation of water, both within an HSU and between HSU's was dependent upon maximizing net agricultural returns for the entire state. Inter-basin transfers of water occur when the value of the marginal productivity in a given HSU was sufficiently high to pay the cost of water transfers, and earn an equal or a higher net profit in the receiving HSU than in the providing HSU. As long as water was available for agricultural use, and a positive net profit was earned, water was allocated to agriculture. If water availability was restricted, it was allocated to the agricultural use and HSU from which the most net profit can be earned.

An optimum solution to the programming model indicated the amount of each variable which was required to maximize statewide profit from agriculture given M&I and wetland requirements. A solution for any given level of M&I or wetland requirement was achieved by making the appropriate changes in coefficients, righthand sides, or bounds. Series of these changes were simulated by parameterizations of the appropriate variables. The model was used to generate the efficient allocations (optimal solutions) for the projected changes in M&I requirements over time, and for alternative requirements for wetland requirements which represented water salvage potentials. [The optimal (efficient) solutions for each alternative parameterizations may be found in Keith et al., (1973).]

The model construction affected the way in which salvaged water was utilized. Since available groundwater limits do not change, the salvaged water was used only as additions to surface water. The model utilized M&I wastewater, originally returned to the surface water flows to meet outflow requirements, for groundwater recharging to provide the least cost water for M&I uses, while natural groundwater could be used in profit-making agricultural production.

Central Utah Project Results

The model's solutions indicated that the development of the Central Utah Project hinges upon several alternative policies with respect to locally available water. Figures 7 through 13 indicate the temporal development of the Central Utah Project. The model indicated that efficient development of the Ute Indian portion of the Central Utah Project would be delayed until some time after 2020, unless use of alternative water sources is restricted. For this reason, discussion of the Ute Indian Unit was not undertaken.

The Sevier Area (SA) portion of the water transfer system did, however, appear efficient at present and develops to its full 22,500 acre-feet/year transfer capability. The transfer consisted of water from HSU 8 transported to HSU 5 using very slightly improved existing facilities. The transfer could be made at less cost than developing new locally available water (King et al., 1972).

The timing of the development of the Bonneville Unit depended to a great extent on the use of alternative locally available water sources as apparent from Figures 7 through 13. The following implications are drawn from the model's results, given the assumptions discussed above.

1. The development of the early stages of the Bonneville Unit is dependent upon water availability in HSU 5. If salvage of water and use of the groundwater reservoir in HSU 5 is allowed up to levels at which groundwater mining occurs, the Bonneville Unit is not economically efficient until 2005 to 2010 for inflows to Great Salt Lake of less than 850,000 acre-feet/year. For inflows of up to 1,014,000 acre-feet/year, postponement of development for 20 years (to 1995) is indicated. With no salvage, low levels of importation are immediately indicated.
2. Development of the Bonneville Unit to full capacity is dependent upon the amounts of available local water in HSU 4. A "take off" of demand for Bonneville Unit water is indicated when groundwater pumping including groundwater recharge reaches a maximum. With water salvage and inflows to Great Salt Lake of 850,000 acre-feet/year, the "take off" occurs between 2015 and 2020, and maximum capacity is not reached prior to the end of the period of analysis (2020); without salvage, the "take off" occurs between 2000 and 2005. For inflows to Great Salt Lake of 1,014,000 acre-feet/year without salvage, the appropriate dates are 1975 to 1980 for "take off" and 1995 for maximum. With salvage, "take off" occurs between 2005 and 2010 and the maximum is not reached until after

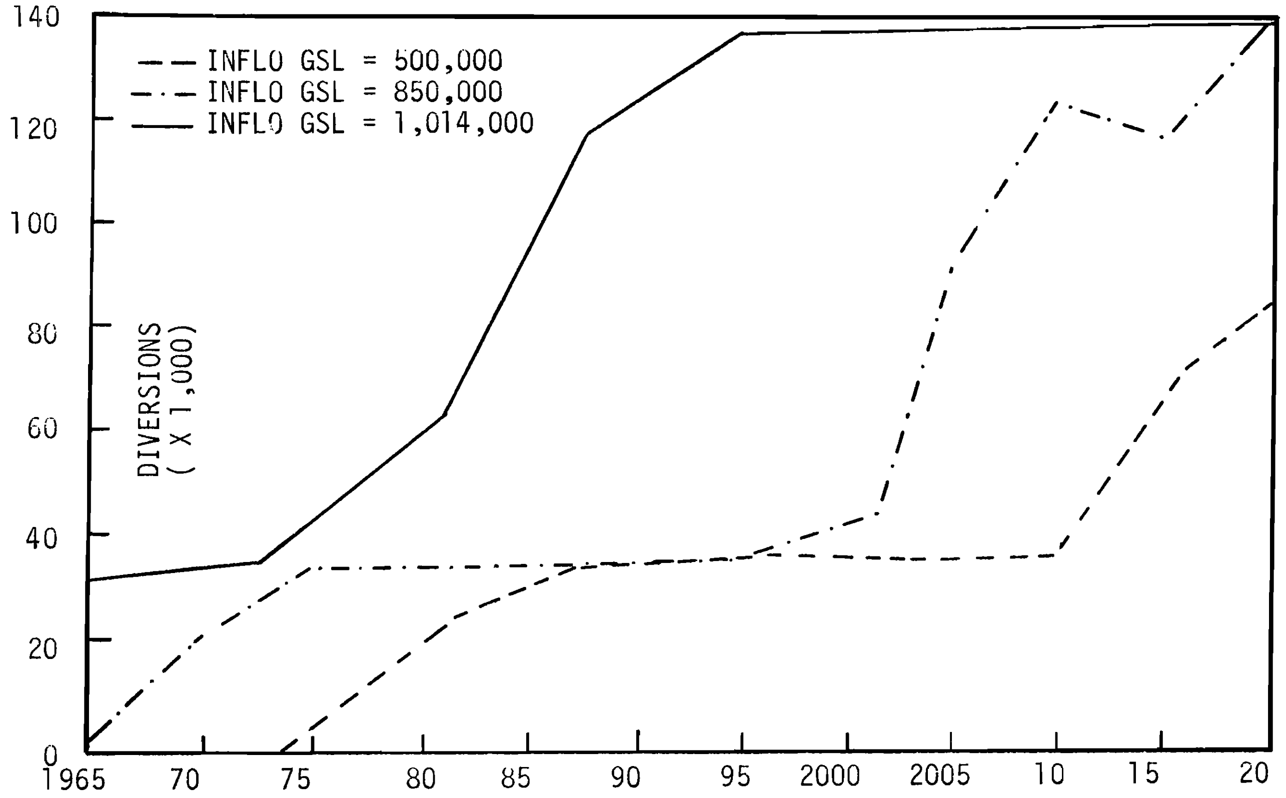

Figure 7. Bonneville Unit diversions with alternative INFLO GSL (no salvage).

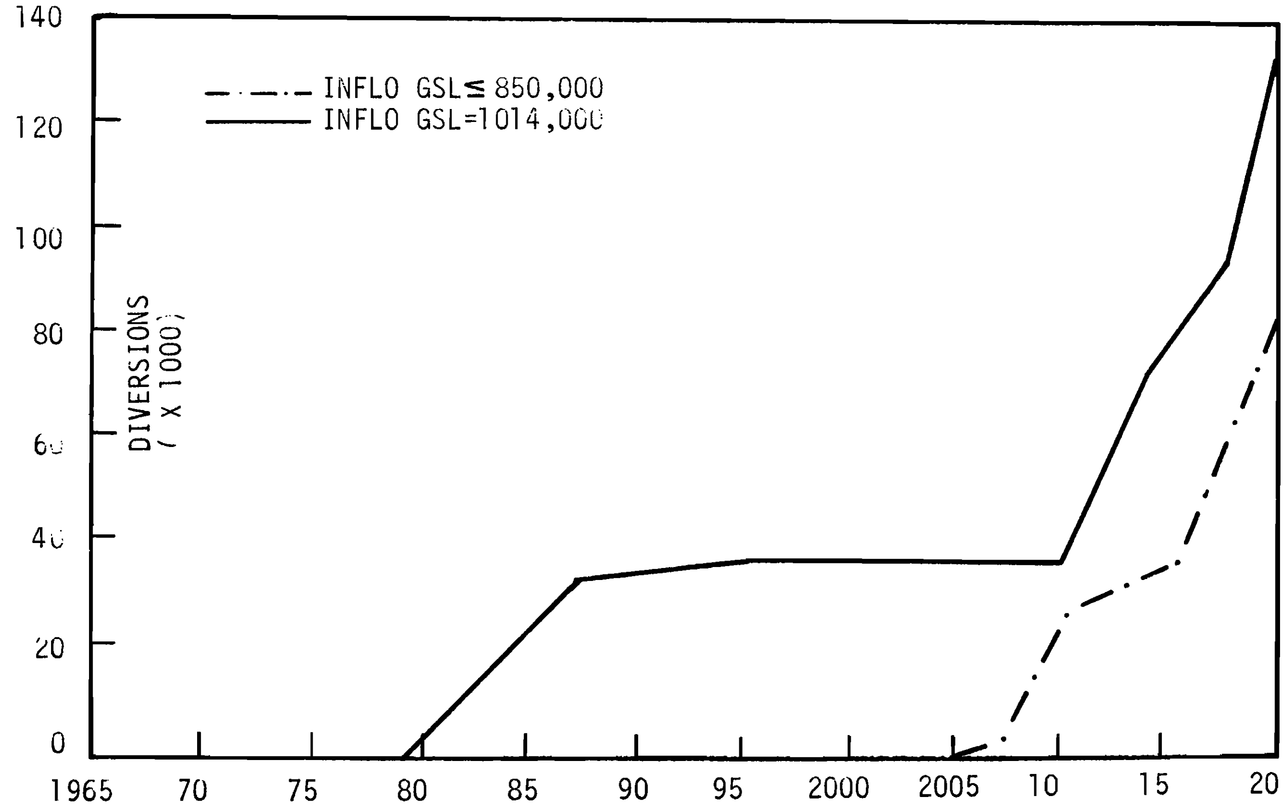

Figure 8. Bonneville Unit cup diversions with alternative INFLO GSL (with salvage).

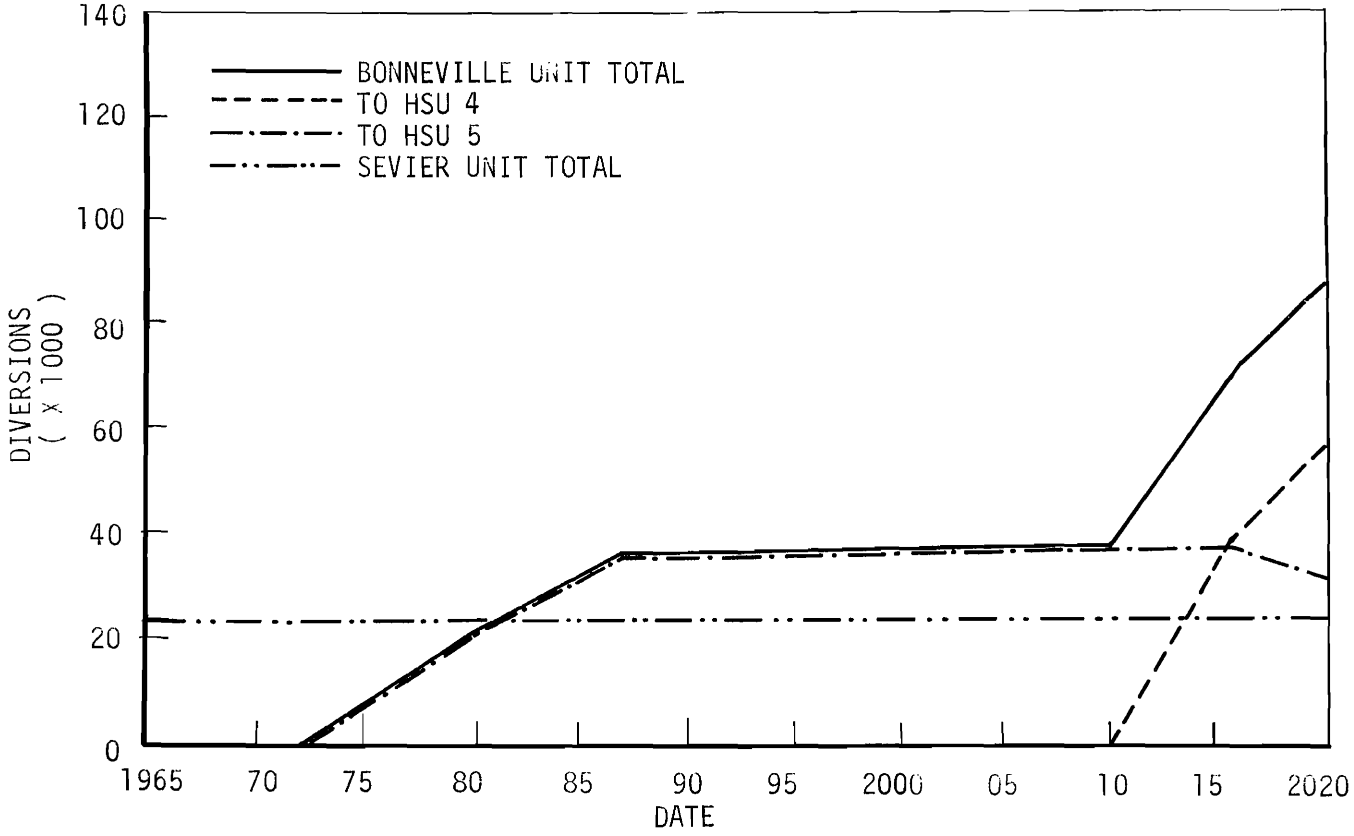

Figure 9. Cup diversions, INFLO GSL 500,000 without salvage.

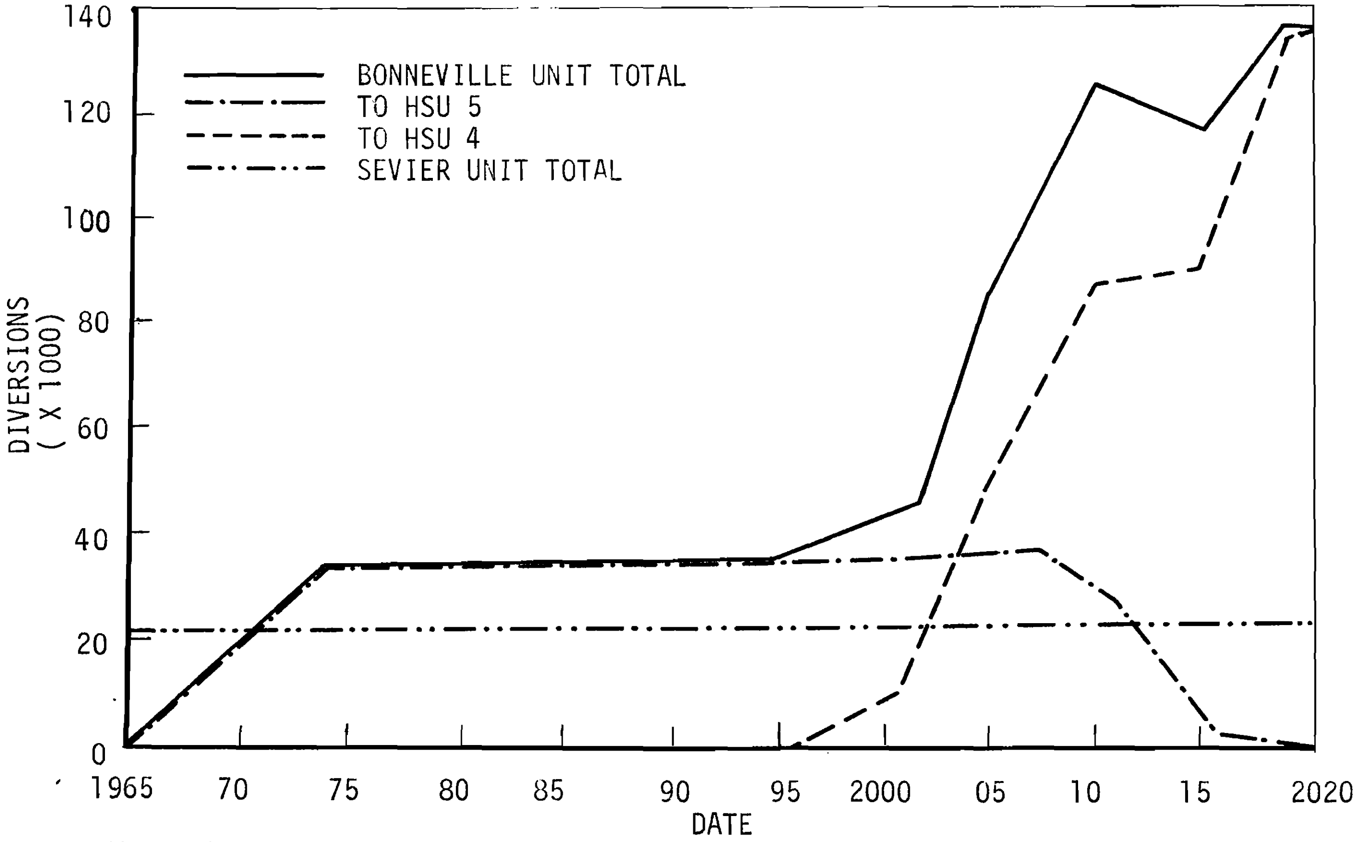

Figure 10. Cup diversions, INFLO GSL 850,000 without salvage.

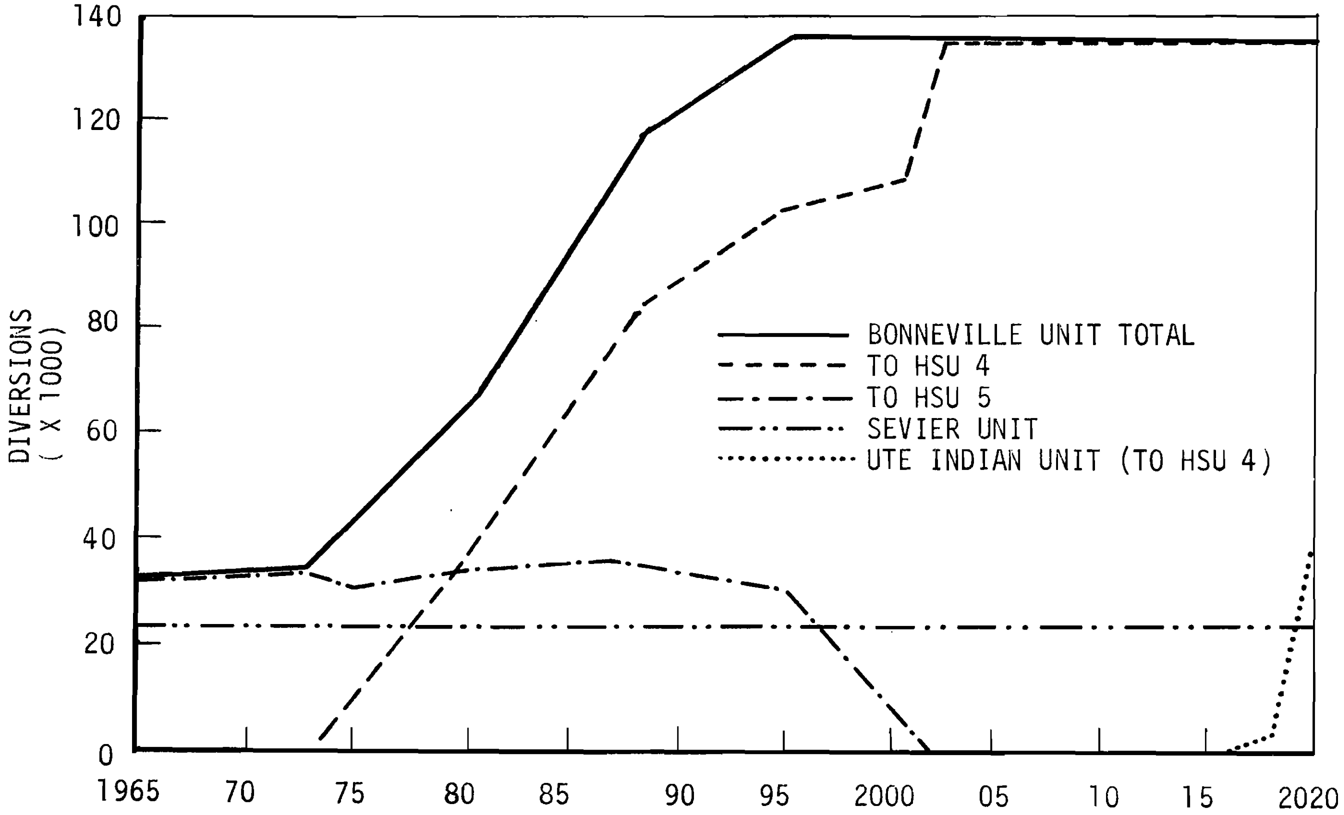

Figure 11. Cup diversions, INFLO GSL 1,014,000 without salvage.

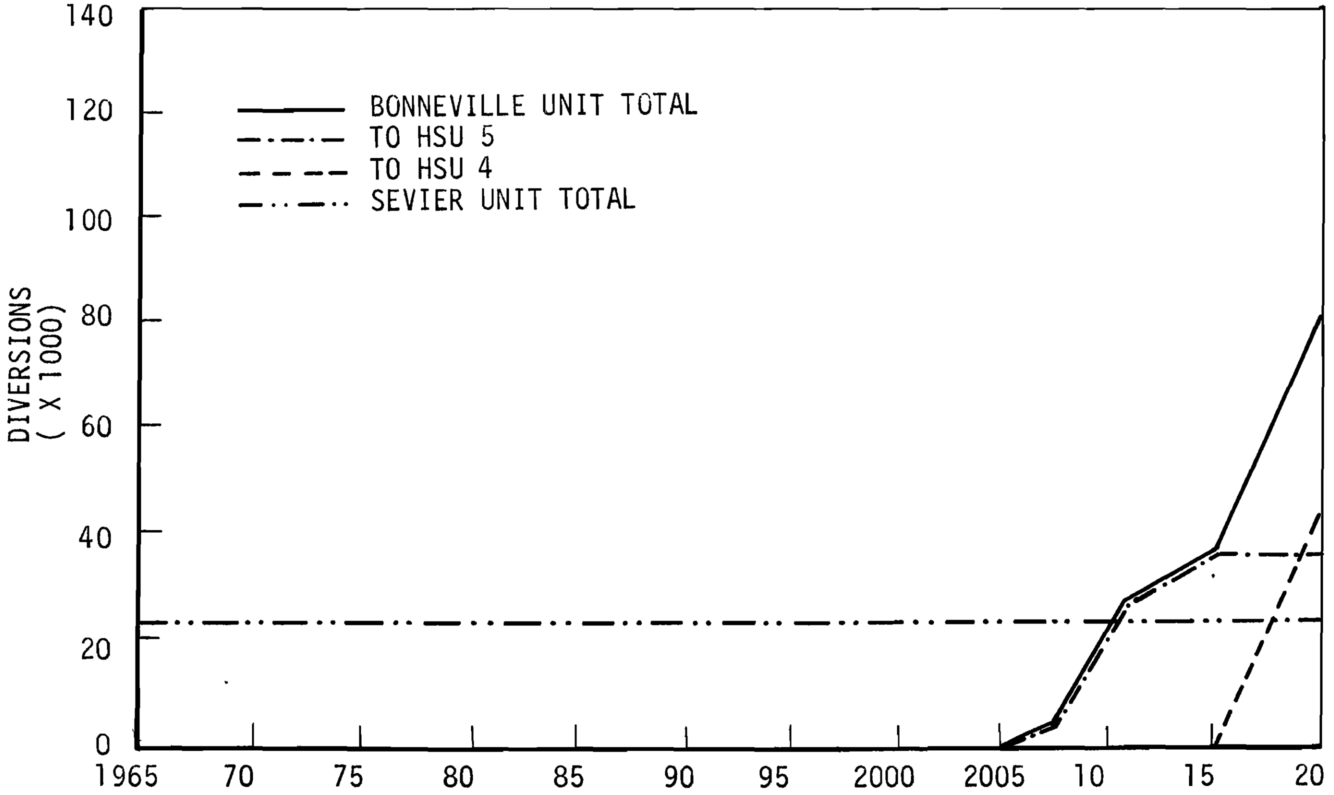

Figure 12. Cup diversions, INFLO GSL 850,000 with salvage.

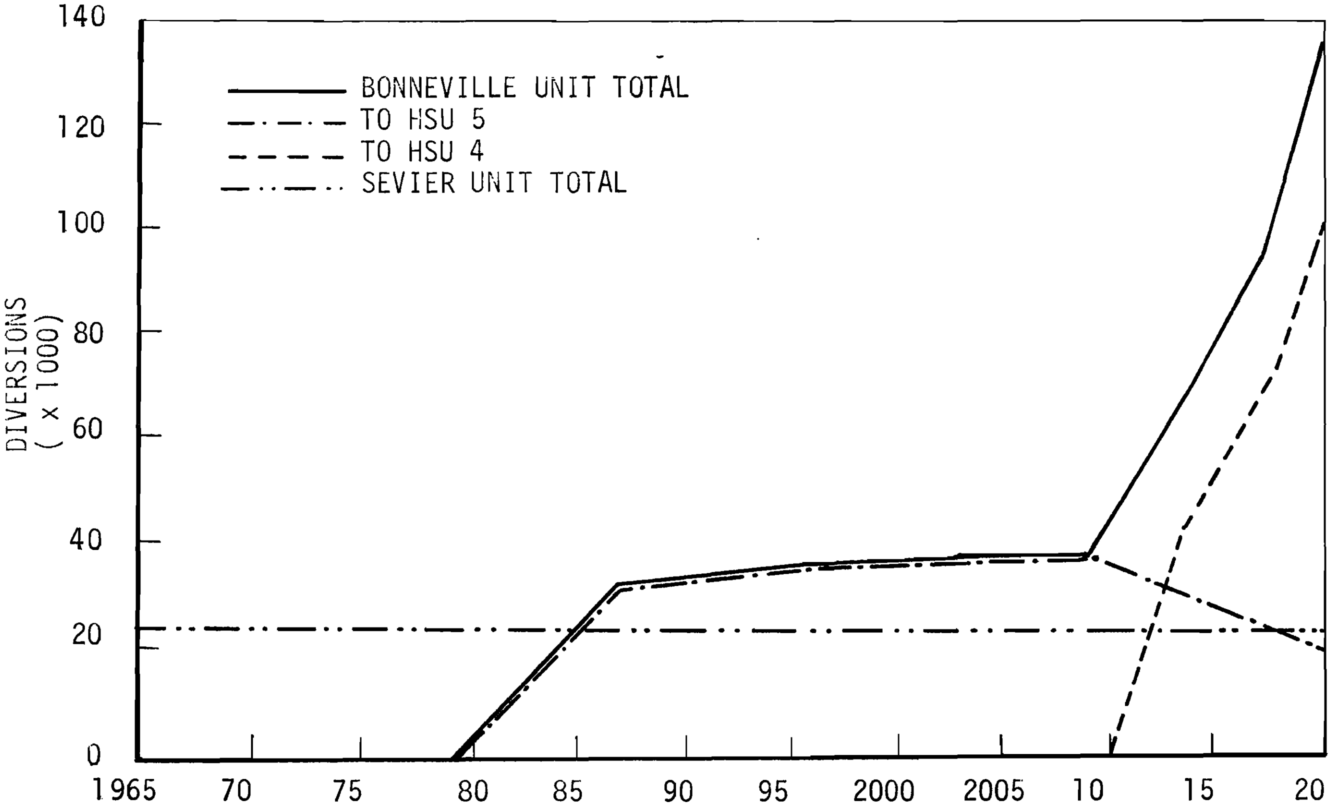

Figure 13. Cup diversions, INFLO GSL 1,014,000 with salvage.

2020 with salvage. Also evident is a decline in allocations to HSU 5 near Bonneville Unit maximum.

3. The use of Bonneville Unit water in HSU 4 depends primarily upon the growth of urban demand (M&I requirements). A comparison of importation timing and agricultural land indicates that Bonneville Unit water is sufficiently costly to be inefficient for new land development. Further, for every solution only available groundwater is sufficiently cheap to provide for new agricultural water. Low cost recharge is utilized for M&I demands and the residual (natural) groundwater storage is used for new agriculture. When M&I requirements exceed the low cost recharge potential (434,000 acre-feet/year) allocation to new agricultural development is reduced by the amount of M&I requirements above recharge potential.[10]
4. Given inflows to Great Salt Lake of greater than or equal to 850,000 acre-feet/year, if groundwater pumping in HSU 4 is limited to present levels by institutional constraints, that is, the present groundwater reservoir levels must be maintained (56,000 acre-feet[11]), the full development of the Bonneville Unit is efficient by 2000 (with salvage; 1990 without).
5. Agricultural practices are limited to present land in HSU 5. It is unprofitable to develop new land with any source of water.
6. There exists a surplus of water in HSU 7 available for transfer by 2020 given even the highest levels of M&I (including oil shale) and agricultural use and maximum Bonneville Unit transfers. The minimum outflow from Utah watersheds to downstream compact states is 350,000 acre-feet/year greater than required to meet the compact minimum [see Keith et al., (1973) Appendix 4(c) (6)]. The HSU 7 outflow is 455,000 acre-feet/year.

Other Results

The model generated water allocations for every HSU, as well as for those involved in Central Utah Project transfer systems. A few general implications for the remaining HSU's are discussed below. [A more complete enumeration may be found in Keith et al. (1973).]

The model indicates that sufficient quantities of water are available to provide relatively large scale agricultural development. However, only in two areas (Bear River and West Colorado) is the quality of land and availability of low cost water sources sufficient to warrant extensive new agriculture. There is some indication (Anderson et al., 1973) that if the most productive agricultural land can be developed with little or no inclusion of less productive land, most HSU's would exhibit some agricultural expansion, although in most HSU's the amounts of new land would be small.

The excess in required outflows to meet the Colorado River user's compact would appear to indicate that full and rapid growth of oil shale and power generation industries would not be limited by water availability. Full development of the oil shale industry would consumptively use about twice the moderate rate of development for a given time period, or about 12,000 acre-feet/year over the present model (an increase in diversions of about 20,000 acre-feet/year). Full development of the power generating industry would increase consumptive use of water by approximately 70,000 acre-feet/year in HSU 8 and about 105,000 acre-feet/year in HSU 9 (diversions would approximately double the consumptive use in both HSU's). Total increased consumptive use (which includes evaporation) is 195,000 acre-feet, or about 155,000 acre-feet/year less than the minimum excess outflow of the alternative assumptions of the present study.

Costs of alternative allocations

The costs of inefficiency were calculated from either foregone returns to investment or the higher costs of supply. Several problems arise in the actual calculations, however. There is a lag between investment and operation resulting from necessary construction time in projects of the magnitude of the Bonneville Unit. Some estimates of the necessary time for construction of the Bonneville Unit range from 10 to 15 years (U.S. Bureau of Reclamation, 1964). Fifteen years was the expected lag assumed in this study. The lag time should provide, in part, for the transfer of small amounts of water as facilities become available. Thus, the efficient allocations of water to HSU 5 were assumed to be achieved by timing development appropriately for full development of the Bonneville Unit. It was further assumed that full investment occurs 15 years prior to the time at which demands equal 75 percent of capacity (102,000 acre-feet/year). This was an arbitrary assumption of optimal timing of investment and development. The model, using this

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[10] It is conceivable that cheaper sources of water, such as groundwater, are profitable enough to pay out the discounted annual costs of land development including water distribution costs (approximately $25.00 per acre in perpetuity) short of perpetuity so that Bonneville Unit water could be efficiently applied to the new irrigated land. There exist two reasons for ignoring this problem. First, profitability in HSU 4 is such that the required period approximates 30 years, at which time most of the Bonneville Unit water will be needed to satisfy M&I demands. Second the encroachment of urban development into agricultural land may reduce significantly the amount of land available for irrigation so that agricultural diversions may remain constant or be reduced in HSU 4.

[11] Calculated by total available groundwater less present use in M&I, wetland use, and groundwater inflows. [272,000 acre-feet - (132,000 acre-feet + 75,000 acre-feet + 8,000 acre-feet)] This corresponds with the free groundwater available to wetlands in HSU 4 minimum of 56,000 acre-feet.

assumption, likely over-estimated the rapidity with which investment in the Bonneville Unit will be required.

Cost of idle investment in the Bonneville Unit

To determine the economic costs of inefficient early investment, it was assumed that all alternatives to transferred water were unrestricted. These alternatives included full groundwater development, inflows to the Great Salt Lake of a minimum of 850,000 acre-feet/year and a maximum water salvage. The appropriate time frame is illustrated in Figure 12. Seventy-five percent of full transfer occurred at approximately the year 2020, and, therefore, the appropriate (assumed) investment date would be 2005. The total returns foregone to idle (unneeded) facilities if investment occurs immediately (1972) was the discounted sum of the annual returns to the investment funds up to 2005, or for the next 32 years. As it was not the purpose of this study to determine the appropriate interest rates, three interest (return) rates were used: 5 percent, the approximate government borrowing rate; 7 percent, the recently suggested discount rate for public investment, and 12 percent, an approximation of the return to private capital.

A conservative estimate of investment costs for the Bonneville Unit attributable to water use (contracted by the Central Utah Water Conservancy District for distribution to M&I and agricultural users) was approximately $130,000,000. Expected annual returns in alternative investments of those funds were $6,500,000 at 5 percent; 9,100,000 at 7 percent; and 15,600,000 at 12 percent.

Over the period of construction, it was assumed that importations of the indicated efficient amounts of water to HSU 5 could be made; that is, the full development of the project would not be needed to provide water imports to HSU 5. There was, therefore, a return to the investment which accrued from payments by water users in HSU 5. If $25.00 per acre-foot (Anderson, 1972) were charged for the delivery of these flows, approximately 40,000 acre-feet/year, the $1,125,000 annual income should be deducted from the foregone returns. The net annual foregone returns were $5,375,000 at 5 percent (a present value of $84,936,000); $7,975,000 at 7 percent (a present value of $100,860,000); and $14,475,000 at 12 percent (a present value of $117,407,000).[12]

If no salvage and inflows of 850,000 acre-feet/year to Great Salt Lake were assumed, Figure 13 indicates the appropriate time for investment is 1990 (2005 less 15 years), or 18 years of foregone returns. The present values for the shorter period of foregone annual returns were $62,834,000 at 5 percent; $80,220,000 at 7 percent; and $104,929,000 at 12 percent.

In any event, the magnitude of the returns which would be foregone on public monies by investing in idle Bonneville Unit facilities is sufficient to offset much of the investment costs. The implication is that mistiming of Bonneville Unit investments may cause a considerable loss of revenue to the public, and should be very carefully analyzed before such investments are made.

Cost of groundwater pumping constraints in the Jordan River HSU

An example of using the study's methodology to determine the cost of institutional constraints can be illustrated by the restriction of groundwater pumping. Costs of providing water and the losses suffered by agriculturalists increased as a result of institutional constraints curtailing any groundwater pumping. Such curtailment is presently practiced along the Wasatch Front to protect head pressures of present wells and preserve maximum groundwater storage. For inflows to the Great Salt Lake greater than or equal to 850,000 acre-feet/year and no salvage, increased low-cost recharge was necessitated and full development of the Bonneville Unit was required in 1995. As a result, two kinds of losses were incurred. First, the users of water suffered higher costs, or losses in producers' surplus. Second, returns to new agricultural development were foregone.

Figure 14 illustrates the annual loss of producers' and consumers' surplus in HSU 4, the appropriate measure for this study since it was in HSU 4 that the timing of the "take off" and full development of the Bonneville Unit were determined. Given the assumptions of inflows to the Great Salt Lake greater than or equal to 850,000 acre-feet/year, no salvage, and groundwater pumping was limited to present quantities, full annual loss of producers' surplus occurred by 2000; the demand curve intersects the supply curve (S^4 in Figure 14) above the price of transferred water at that time. Estimates of annual losses of surplus were made for each 10-year period, beginning in 1980 and ending in 2020, after which all annual losses were equal. Since there was no groundwater applied to present agricultural production in HSU 4, only M&I uses suffered increased costs. The supply curve without restrictive constraints is the S^4 curve and the supply curve with

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[12] Factors for 32 years are: 15.802 at 5 percent, 12.645 at 7 percent; 8.111 for 12 percent. 18 years are: 11.690 at 5 percent; 10.059 at 7 percent, 7.249 for 12 percent.

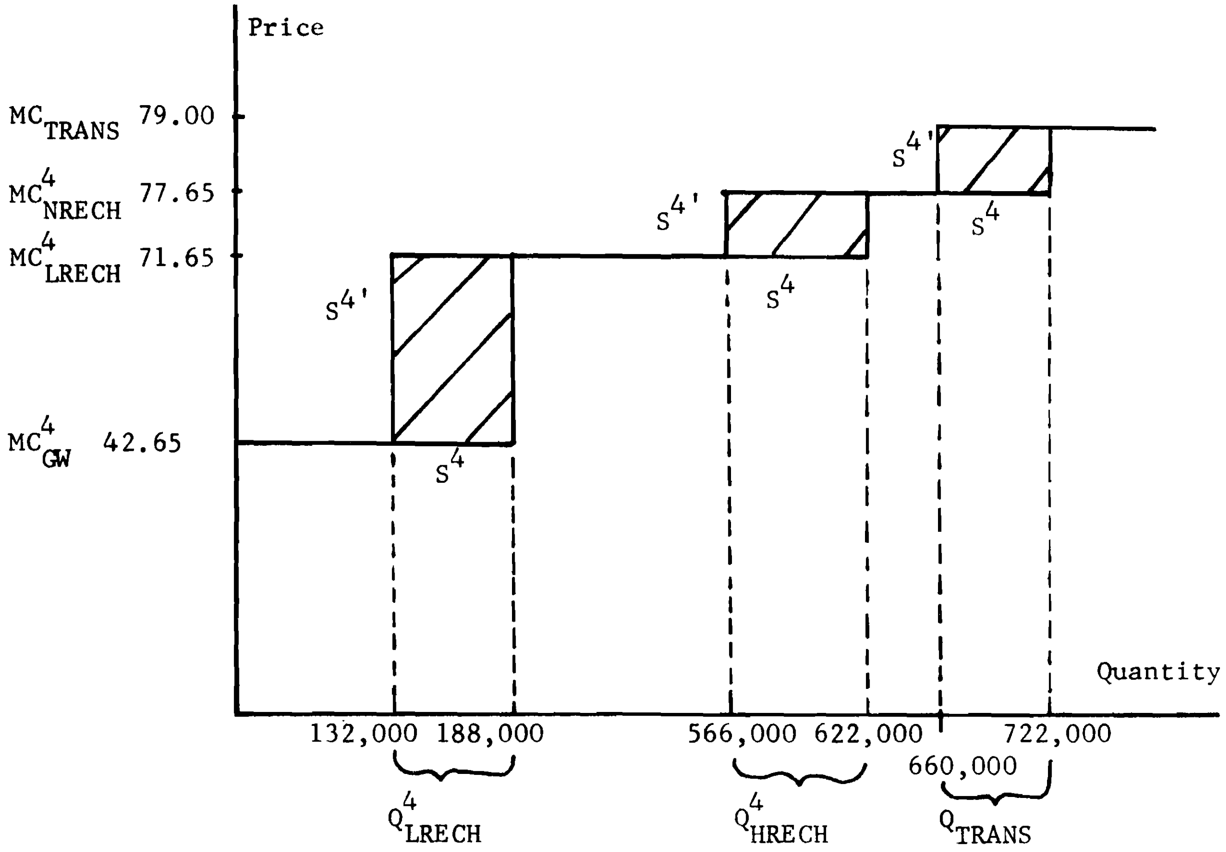

Figure 14. Losses in consumers' and producers' surplus in HSU 4.

restrictive constraints is the $S^{4'}$ curve.[13] The crosshatched areas define the losses in producers' and consumers' surplus in HSU 4 as a result of the higher marginal cost curve. Table 13 is a tabulation of the losses of producers' surplus as indicated in Figure 14. The calculation of the losses of producers' surplus to M&I uses for a given period, therefore, is:

$$(7)\ (MC^4_{LRECH} - MC^4_{GW})(Q^4_{LRECH}) + (MC^4_{HRECH} - MC^4_{LRECH})(Q^4_{HRECH}) + (MC^4_{TRANS} - MC^4_{HRECH})(Q_{TRANS})$$

The additional loss of benefits of producers' and consumers' surplus accruing to new agriculture which were foregone are minimally estimated by the gross returns less the cost of new groundwater diversions to agriculture multiplied by the quantity of new groundwater applied to new land (net returns to new agriculture). Restriction of salvage increased losses of returns since salvage releases additional groundwater for use in new agricultural production Mathematically:[14]

$$(8)\ (TR^4_{AG} - MC^4_{GW})(Q^{4NEW}_{GW})12$$

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[13] The following symbols used in Figure 14 are defined as:

MC_{TRANS} = Marginal cost of transferred water
MC^4_{LRECH} = Marginal cost of low-cost recharge in HSU 4
MC^4_{HRECH} = Marginal cost of high-cost recharge in HSU 4
MC^4_{GW} = Marginal cost of new groundwater in HSU 4
Q^4_{LRECH} = Quantity of low-cost recharged water to replace new groundwater
Q^4_{HRECH} = Quantity of high-cost recharge to replace low-cost recharge
Q_{TRANS} = Quantity of water transferred to replace high-cost recharge
Q^4_{GW} = Quantity of new groundwater used in HSU 4 on M&I requirements

[14] Q^{4NEW}_{GW} = Quantity of new groundwater used for new agricultural production (with salvage)
TR^4_{AG} = Total revenue to new agricultural production per acre-foot in HSU 4

Table 13 indicates the present value of the losses of producers' surplus to institutional constraints.[15] Table 14 indicates the losses of benefits to new irrigation.

The present value of the losses is the sum of the discounted values of annual costs or losses over the appropriate periods. Note that producers' surplus losses were increasing over time and that the losses were decreasing for new agricultural applications. Discounting M&I surplus losses was done using the minimum cost for the period, but for new agricultural the average loss per period was used.

Total present value of the economic costs of institutional constraints on groundwater pumping and restricted water salvage were $27,971,000 at 5 percent; $24,217,000 at 7 percent; and $11,659,000 at 12 percent. The losses were underestimates, since the 1972 to 1980 period was not covered due to lack of solutions for that period. In any event, relaxing the institutional constraints on use of locally available water would provide benefits to society which are of magnitude sufficient to pay off significant amounts of the investment costs in the Bonneville Unit, particularly at lower interest rates.

If public policy is both to limit the development of locally available water and to invest now so that the returns are zero until 1985, the economic costs were even higher. Both loss of returns and loss of benefits must be taken into account. At 5 percent, the present value of the annual loss was approximately $30,000,000 and the value of foregone returns are approximately $60,000,000. Total loss approximated $90,000,000 or about 70 percent of the cost of the project as contracted by the Conservancy District.

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[15] Factors are:
Present value $1 per annum:
10 years: 7.728 at 5%; 7.023 at 7%; 5.650 at 12%
Discount present value 1
8 years .677 at 5%; .582 at 7%; .404 at 12%
18 years .416 at 5%; 296 at 7%; .130 at 12%
28 years: .255 at 5%; .150 at 7%; .042 at 12%
38 years: .157 at 5%; .076 at 7%; .013 at 12%

Table 12. Calculations of annual economic costs of institutional constraints on uses of locally available water in HSU 4.

Year	Beginning Period	MC^4_{TRANS}	MC^4_{LRECH}	MC^4_{HRECH}	MC^4_{GW}	MC^{4NEW}_{GW}	Q^4_{LRECH}	Q^4_{HRECH}	Q_{TRANS}	Q^{4NEW}_{GW}	Annual Loss M&I	Annual Loss Ag
1980	M&I	79.00	71.65	77.65	49.65		56,000		0		1,232.000	
	AG					6.50[a]				256.000		1,599,000
1990	M&I	79.00	71.65	77.65	49.65		56.000	27.000			1,394,000	
	AG					6.50				201,000		1,306,500
2000	M&I	79.00	71.65	77.65	49.65		56,000	36,000			1,568,000	
	AG					6.50				134,000		871,000
2010	M&I	79.00	71.65	77.65	49.65		56.000	56.000	56,000		1,643,000	
	AG					6.50				0		0

[a] Total revenue per acre foot of $13.00 less costs of new groundwater to agriculture which include $3.00 per acre foot groundwater distribution, $1.00 per acre foot on farm operation and maintenance cost, and a minimum estimate of $2.50 per acre foot land development cost (10.10 per acre ÷ 4 acre feet/acre water application).

Table 13. Present value of producers' surplus losses.

Interest Rate	Period Beginning	Present Value at Period Beginning		Present Value Discounted to 1972
5%	1980	9,521,000		6 446,000
	1990	10,773.000		4,482,000
	2000	12,118,000		3,090.000
	2010	12,702.000		1.994,000
			TOTAL	16,012.000
7%	1980	8 652,000		5,035,000
	1990	9,790,000		2,898,000
	2000	11,012,000		1.652.000
	2010	11,543,000		877,000
			TOTAL	10,462.000
12%	1980	6,961.000		2,812,000
	1990	7 876,000		1.024,000
	2000	8,859,000		372,000
	2010	9,286,000		121,000
			TOTAL	4,329,000

Table 14. Present value of losses to new irrigation.

Interest Rate	Period Beginning	Present Value at Period Beginning		Present Value Discounted to 1972
5%	1980	11,227,000		7,601,000
	1990	8,414,000		3,500,000
	2000	3,366,000		858,000
	2010	0		0
			TOTAL	11.959,000
7%	1980	10,203,000		5,938.000
	1990	7,646,000		2,263,000
	2000	3,059,000		459,000
	2010	0		0
			TOTAL	8,660,000
12%	1980	8,208,000		3,160,000
	1990	6,151,000		800,000
	2000	2,461,000		103,000
	2010	0		0
			TOTAL	4,063,000

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The study in general and development of the model in particular have led to several conclusions with respect to the general research approach:

1. The inclusion of demand and supply analyses as separate components avoids the problems involved in least-cost planning for projected demands. While this study did project M&I demands, using demands in the marginal, or least productive, activity did indicate that agricultural use changed as costs rose. The writers suggest inclusion of demand studies in all planning and feasibility studies where possible. The "requirements" approach to water planning lacks consideration of one-half the problems.
2. Multiple demands can be usefully included in a mathematical programming model so that efficient allocations among uses can be determined directly. In this model, the trade offs among water uses (agricultural, municipal and industrial, and wetlands) were evaluated.
3. Costs of policies which deviate from efficient (or optimal) allocations can be determined using supply functions, demand functions, or both, from mathematical programming. From these costs, public decision-makers can readily and clearly analyze results of alternative decisions.
4. Hydrologic modeling can be effectively included in a mathematical programming allocation model, although some of the relationships must be generalized. The accuracy of the reproduction of the hydrologic system relationships is determined by the scope of the mathematical programming modeling effort.
5. Models similar to the one developed for Utah can be constructed for other areas, states, or regions. These models can effectively provide analyses of resource allocation decisions which involve costs of much greater magnitude than the cost of developing the model. We believe this approach is a reasonable compromise between the high cost of planning and the need for detailed information.
6. Once the model is constructed, changes in structure or coefficients can be carried out at little cost relative to their usefulness in planning.
7. Interdisciplinary research can be productive, particularly when a model such as this is the focus of study. Information exchange and cooperation can develop from developing such models, in part because of the requirements for structuring the model.

Some specific conclusions were reached concerning allocations of water in Utah:

1. The timing of development of the Bonneville Unit of the Central Utah Project is dependent upon the growth of M&I requirements for water in the Jordan River area, and upon the use of locally available alternative water sources, such as interception of inflows to the Great Salt Lake.
2. The cost of mistiming investment of public monies in the Bonneville Unit is of sufficient magnitude to warrant careful and explicit consideration of alternatives and requirements by public officials. If goals other than economic efficiency dictate inefficient allocations, then the costs which occur must be born by those goals.
3. Locally available water is not a limiting factor for economic growth in most HSU's, although the Sevier River area does appear to require some importation. M&I increases, including oil shale development and power generation plants, can be supported simultaneously with efficient agricultural expansion by existing water sources. In general, the value of water in agriculture is apparently too low to warrant development of elaborate and expensive transfer systems.

Recommendations for Further Research

There appear to be at least four areas in which the model and the research approach in general could be improved.

First, the cooperation between public officials, responsible for decisions concerning water or other resource planning, and researchers could be improved. The benefits will be two-fold The research and model will include the variables and coefficient values which decision-makers feel are appropriate, as well as those chosen by researchers. Modifications of the model using public decision-makers inputs should lead to better understanding and utilization of the output of research efforts in public policy formulation.

Second, while quantity of water available was of course critical, quality of water may effectively limit water availability and, therefore, efficient allocations. For example, if quality standards are established by the Colorado River Compact for the outflow of water from Utah, industrial and agricultural treatment of return flows may be required, adding to costs and/or lessening demands. Quality standards for return flows in the Great Basin HSU's may similarly be reflected in allocations. The addition of quality constraints and alternative standards should be a prime goal of further research.

Third, the inclusion value of marginal product curves for M&I uses would make the model more truly allocative. Until the demand schedule for M&I water is known, the effect of the increased costs of M&I and agricultural transfers and quality requirements cannot be accurately judged. Further research is definitely required if the model is to indicate efficient allocations. The inclusion of such demand curves could enable more precise establishment of trade-offs between various sectors of the economy. Further, multiple goals could be added to the objective function or the constraint system to generate more information for decision-makers.

Finally, the coefficients used in the model were taken as constants, even though they are drawn from stochastic distributions. The effect of the variability (uncertainty) of the coefficients on the solution is not known. Stochastically programming at least portions of the model in which large variability occurs is a desirable goal for further research, and should provide a better knowledge of the model's applicability to problems in resource allocation.

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APPENDIX 1

PRESENT STATUS OF WATER RESOURCE DEVELOPMENT

A summary of the status of water resource development in the State of Utah is shown in Table 5. Explanation and reference information are given in the following paragraphs.

1. Basin Yield These data are the same as shown previously in Table 2.
2. Net Evaporation Loss Large Lakes These data show the loss of water as a result of evaporation from Bear Lake in HSU 2 and from Utah Lake in HSU 4. Account was taken of the precipitation on the lake surface to calculate the net loss. Since about one-half of the surface area of Bear Lake is in Idaho, only one-half the net evaporation loss was charged to Utah. Water budget studies were used to determine the loss which was divided between surface and groundwater.
3. Net Evaporation Loss Other Major Reservoirs These data were determined as discussed in 2 except in HSU 5 where the loss was distributed 75 percent to surface water and 25 percent to groundwater and HSU 7 and 8 where no groundwater is available.
4. Storage Capacity – Storage capacity data were taken from several sources:
   - a. An early report on the state water plan (Utah State University - Utah Water and Power Board, 1963);
   - b. Investigations by the Utah Division of Water Resources; and
   - c. Investigations by the Pacific Southwest Inter-Agency Committee, U. S. Water Resources Council (Water Resources Work Group, 1971).
5. Direct Use of Groundwater by Croplands – It is recognized that this occurs in all HSU's however these data were only calculated in the water budget for the Sevier Basin (United States Department of Agriculture - Utah Department of Natural Resources, 1969). It was included there as a reduction in the available groundwater to make the data compatible in all HSU's.
6. Excess Precipitation on Irrigated Croplands, October-April - These data were determined from the hydrologic inventories for HSU 2, 3, 4, 5, and 7 The values represent the amount of precipitation which is in excess of the amount consumptively used by the crops. This represents an addition to the water supply since it would appear as runoff in the streams or an addition to groundwater.
7. Transbasin Diversions These data were obtained from the same sources as Table 2.
8. Gross Supply – These data are the summation of: basin yield; net evaporation loss large lakes; net evaporation loss other major reservoirs; direct use of groundwater by croplands; excess precipitation on irrigated croplands, October-April; and net imported water from transbasin diversions.
9. In-Basin Water Availability These data are the summation of: basin yield; net evaporation loss large lakes; direct use of groundwater by croplands; and excess precipitation on irrigated croplands, October-April.
10. Present Diversions – Total diversions to agriculture and to municipal and industrial for HSU 2, 3, 4, 5, and 7 were taken from the hydrologic inventories referenced on Table 2. Total diversions to the other five HSU's were based primarily on data from Utah Division of Water Resources except where modified to account for studies conducted by the Utah Water Research Laboratory. Groundwater pumpage was determined by using the average figure from 1964-1968 given in the yearly reports on groundwater conditions in Utah (Utah Division of Water Resources - United States Department of the Interior, Geological Survey, 1965-1969) Surface water diversions were obtained by subtraction.
11. Return Flows – Return flows for HSU 2, 3, 4, 5, and 7 were obtained from the hydrologic inventories. Agriculture return flows for HSU 1, 6, 8, and 10 were based on Utah Division of Water Resources data while for HSU 9 was based on Utah Water Research Laboratory studies. Municipal and industrial return flows for HSU 1 and 6 were based on Utah Division of Water Resources data whereas for HSU 8, 9, and 10 they were based on approximations to the expected return flow coefficients projected by Utah Division of Water Resources for the year 2020.

12. Depletions other than Reservoir Evaporation -- Depletions for HSU 2, 3, 4, 5, and 7 were based on the hydrologic inventories while for HSU 1, 6, 8, 9, and 10 they were based on Utah Division of Water Resources data. The division between surface and groundwater was determined using individual budgets for each knowing the groundwater outflow. It is recognized that much of the water in the upper areas of the river basins which is below ground may rise to the surface in the lower areas and be consumed by wetlands, etc. This fact is reflected by the large depletions of groundwater by wetlands.

13. Outflow from HSU – The groundwater outflow to Great Salt Lake from HSU 1, 2, 3, and 4 was estimated using the results of several studies conducted on this subject by Utah Water Research Laboratory and others. HSU 5 and 6 have groundwater mining which is shown by negative outflow. Groundwater outflow for HSU 7 was obtained from the water budget study Surface water outflow was determined by balancing water availability, depletions, and groundwater outflow.

4. Colorado River Water Transfer Provisions have been made in the model for the transfer of additional Colorado River water into the Great Basin. This water is supplied by two units of the Central Utah Project, the Bonneville Unit, and the Ute Indian Unit; and by an additional small amount from HSU 8 designated as the Sevier Area. The water transferred by the Ute Indian Unit can be used in HSU 3, 4, and 5 while that from the Bonneville Unit and Sevier Area is transferred to HSU 4 and 5. The transferred water was assumed to be released into the local surface water pool.

Table 5. Status of water resource development in Utah. (Units in thousands of acre-feet/year except storage)

Hydrologic Study Unit	Basin Yield			Net Evaporation Loss Large Lakes			Net Evaporation Loss Other Major Reservoirs			Storage Capacity	Direct Use by Cropland	Excess Precipitation on Irrigated Croplands, Oct-Apr			Transbasin Diversions		
	Surface Water	Ground-water	Total	Surface Water	Ground-water	Total	Surface Water	Ground-water	Total	(ac-ft)	Ground-water	Surface Water	Ground-water	Total	Imported Water	Exported Water	Net Imported Water
1	613	187	800	-	-	-	1	0	1	17					0	10	10
2	917	138	1,055	42	41	83[a]	2	1	3	311		66	7	73	19	0	19
3	660	65	725	-	-	-	13	13	26	578		129	30	159	0	90	-90
4	560	394	954	131	132	263[b]	13	13	26	416		85	10	95	182	0	182
5	417	356	773	-			45	15	60	481	105	37	4	41	11	4	7
6	80	130	210	-	-	-	3	1	4	56		-			3	0	3
7	1,319	40	1,359	-	-	-	12	0	12	428[c]		33	0	33	0	101	101
8	650	0	650	-	-		9	-	9	199					0	11	11
9	430	0	430	-	-	-	-	-		1	-				4	0	4
10	250	10	260	-	-	-	1	0	1	14	-				0	3	-3
Total	5,896	1,320	7,216	173	173	346	98	43	142	2,501	105	350	51	401	219	219	0

Hydrologic Study Unit	Gross Supply			In-Basin Water Availability			Diversions							Return Flow				
							To Agriculture			To Municipal & Industrial			Total Diversion	From Agriculture			From M&I	Total Return Flow
	Surface Water	Ground-water	Total	Surface Water	Ground-water	Total	Surface Water	Ground-water	Total Ag	Surface Water	Ground-water	Total M&I		To Surface	To Ground	Total Ag	Only to Surface	
1	602	187	789	613	187	800	105	19	124	7	3	10	134	59	6	65	7	72
2	959	102	1,061	941	104	1,045	1,015	19	1,034	36	8	44	1,078	628	52	680	29	709
3	686	82	768	789	95	884	610	33	643	29	21	50	693	375	32	407	22	429
4	683	259	942	514	272	786	714	83	797	171	132	303	1,100	447	40	487	208	695
5	416	240	656	453	255	708	890	128	1,018	7	10	17	1,035	636	51	687	8	695
6	80	129	209	80	130	210	136	64	300	10	3	13	313	148	15	163	9	172
7	1,238	40	1,278	1,352	40	1,392	789	0	789	10	0	10	799	496	0	496	6	502
8	630	0	630	650	0	650	303	0	303	7	0	7	310	189	0	189	2	191
9	434	0	434	430	0	430	150	0	150	7	0	7	157	120	0	120	2	122
10	246	10	256	250	10	260	68	0	68	2	0	2	70	34	0	34	1	35
Total	5,974	1,049	7,023	6,072	1,093	7,165	4,780	446	5,226	286	177	463	5,689	3,134	196	3,329	294	3,623

Hydrologic Study Unit	Depletions Other Than Reservoir Evaporation												Outflow From Hydrologic Study Unit		
	For Agriculture			For Municipal & Industrial			For Wetlands			Total Depletions					
	Surface Water	Ground-water	Total	Surface Water	Ground-water	Total	Surface Water	Ground-water	Total	Surface Water	Ground-water	Total	Surface Water	Ground-water	Total
1	46	13	59	0	3	3	549	165	714	595	181	776	7	6	13
2	387	-33	354	7	8	15	118	122	240	512	97	609	447	5	452
3	235	1	236	8	20	28	107	36	143	350	57	407	336	25	361
4	267	43	310	-38	132	94	274	76	350	503	251	754	180	8	188
5	254	77	331	-1	10	9	149	184	333	402	271	673	14	-31[d]	-17
6	-12	149	137	1	3	4	91	35	126	80	187	267	0	-58[d]	-58
7	293	0	293	4	0	4	315	0	315	611	0	611	627	40	667
8	114	0	114	5	0	5	36	0	36	155	0	155	475	0	475
9	30	0	30	5	0	5	8	0	8	43	0	43	391	0	391
10	34	0	34	1	0	1	9	10	19	44	10	54	202	0	202
Total	1,647	250	1,897	-8	176	168	1,657	627	2,284	3,295	1,053	4,348	2,679	-5	2,674[e]

[a] One-half of total Bear Lake net evaporation.

[b] All of Utah Lake.

[c] Includes Strawberry Reservoir (283,000 ac-ft).

[d] Reflects groundwater mining.

[e] Reflects 1,014,000 ac-ft per year inflow to Great Salt Lake from Utah watersheds.