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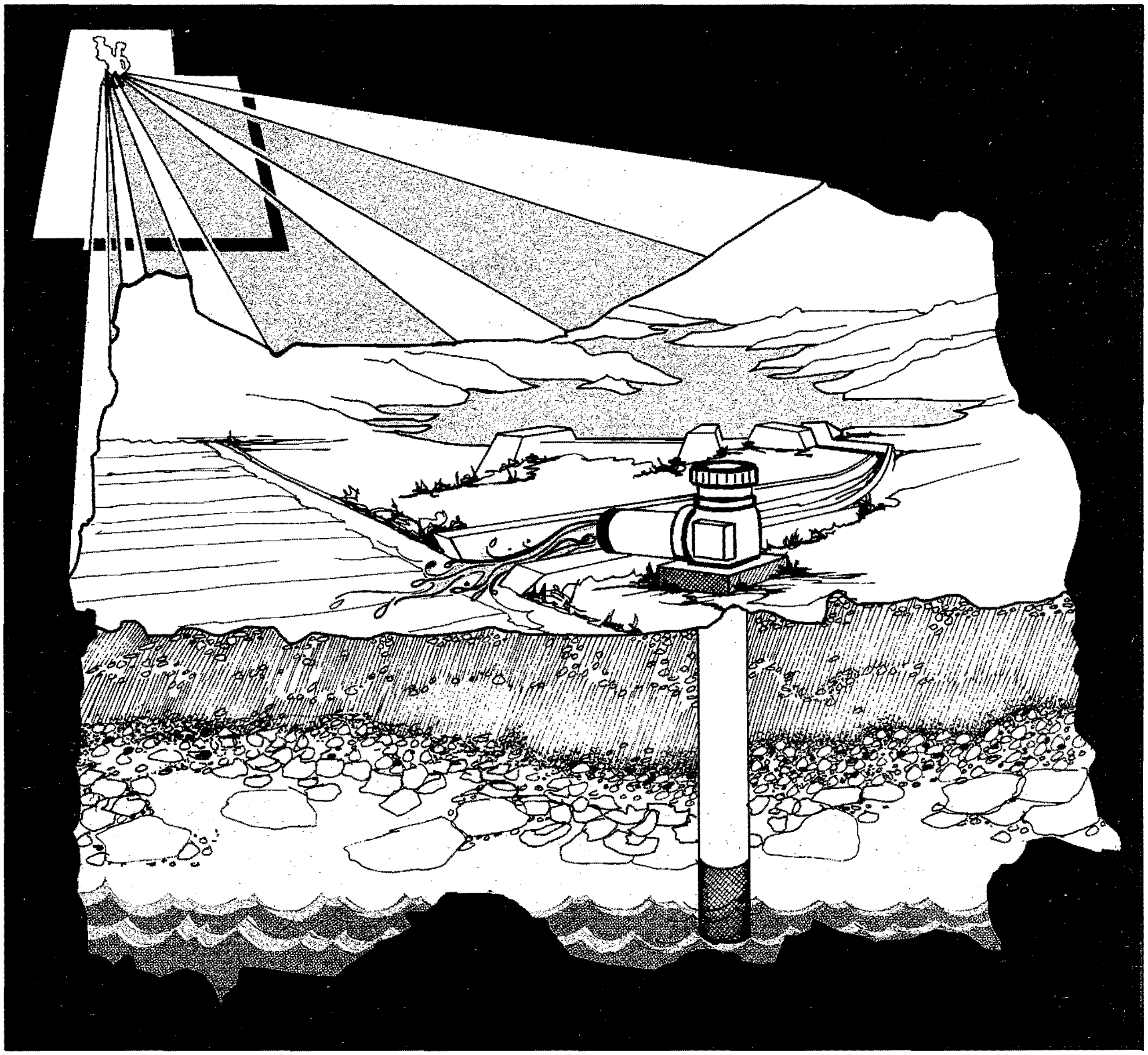

Utah Water Research Laboratory
Utah State University
Logan, Utah 84322

WATER RESOURCES PLANNING SERIES
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CONJUNCTIVE WATER USE PLANNING WITH WATER QUALITY CONSTRAINTS

IN TOOELE VALLEY, UTAH

by

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ABSTRACT

The need for more efficient water management is gaining recognition due to the increased cost of water supply, the growth in the demand for water, and greater environmental and social impacts of water programs. "Conjunctive use" of surface and groundwater resources provides opportunities for increasing net benefits to the water users. Past "conjunctive use" studies, however, have usually not included water quality constraints.

In Tooele Valley, Utah, spatial variation of groundwater quality (total dissolved solids) is significant. The areas of good (400-500 mg/l), fair (500-1,000 mg/l), and poor (1,000-3,000 mg/l) quality groundwaters were identified in an earlier study by the USGS. The water quality dimension was incorporated into the conjunctive use planning to account for crop yield changes due to changes in salinity levels in irrigation water. The possibilities for increasing total net benefits by blending surface and groundwaters of different qualities were examined by developing a linear programming optimization model.

The optimization model provides for mixing the different qualities of water available and the crops to maximize benefits. It applies linear programming to the Tooele Valley water supply system and optimizes over three locations, four crops, and five qualities of water of differing costs. The groundwater withdrawals at the locations dictated by the optimization model were input to the Tooele Valley groundwater simulation model developed by USGS to study the effects on the valley's principal artesian aquifer.

Economic analyses of the probable scenarios of future agricultural development in Tooele Valley did not suggest that extensive increases in groundwater withdrawals will occur. Economic infeasibility of major increases in groundwater extraction is a limiting factor for agricultural development in most parts of the valley. Groundwater mining therefore does not seem like a major future problem.

The areas where new wells can be drilled without interference causing technological diseconomies are indicated. Profitable application of blending technology to irrigated agriculture in Tooele Valley is not possible without making a drastic shift to some higher valued crop such as fruit trees. All surface water sources should be fully utilized before developing additional and expensive groundwater. Even though an additional 20,000 to 25,000 ac-ft of groundwater can be extracted without mining, there would be a high risk of destroying natural phreatophyte habitats and degradation of water quality in at least some parts of the artesian aquifer.

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CHAPTER I

INTRODUCTION

The need for more efficient management of available water resources is increasing with the greater cost of water supply and the growth in demand for water. Traditionally, surface and groundwater have been pictured as two independent sources for supplying water. However, systems optimization studies have shown that "conjunctive use" planning, where surface and groundwater are considered interdependent components of a single system, reduces water supply costs, thus increasing the total net benefits derived from the use of water.

The concept of conjunctive use of groundwater and surface water resources originated in the late 1940s in the arid western United States in response to the water problems of that period. Today, the conjunctive use concept has been widely accepted by water resource planners and is considered prerequisite to optimal water utilization.

According to Todd (1980, p. 371), "The concept of conjunctive use of surface and groundwater is predicated on surface reservoirs impounding streamflow, which is then transferred at an optimum rate to groundwater storage. Surface storage in reservoirs behind dams supplies most annual water requirements, while the groundwater storage can be retained primarily for cyclic storage to cover years of subnormal precipitation. Thus, groundwater levels would fluctuate, being lowered during a cycle of dry years and being raised during an ensuing wet period." The feasibility and usefulness of conjunctive water use planning, therefore, depends on the hydrologic and geologic characteristics of the basin.

Conjunctive use may be implemented in a number of other ways as well. Another example is a situation where good quality surface water is available in limited quantity, whereas, poor quality groundwater is relatively plentiful. Here, artificial recharge using the good quality surface water would deteriorate its quality. The concept of "conjunctive use" or, alternatively, "coordinated use" would blend waters from the two sources of differing qualities to obtain more water of a lesser, but acceptable quality. The blending should vary with the relationship between yield and water quality for a particular crop and soil.

The present study seeks to determine if and how coordinated water use planning can help the farmers in Tooele Valley, Utah. Optimization and simulation techniques are used to allocate groundwater and surface water resources of different qualities among various uses to maximize the present value of net benefits. The present value of net benefits is defined as the market value of agricultural outputs, net of all variable costs incurred in every time period, discounted to the present value using an appropriate discount rate. It can also be interpreted as the discounted present value of rent accruing to land and water resources of different quality in the groundwater basin.

For the renewable surface water resource, the benefit-maximizing quantity can be determined by equating marginal benefits to the marginal cost of water. The optimization can be handled by linear programming techniques when several agricultural products are produced using water from different sources. The problem becomes more complex when groundwater mining increases the cost of pumping. The water left in storage has economic value through reducing the pumping lift and being available for future use. In such a situation, a decision made in one time period has a cost that continues through the following periods. In order to reach an optimal policy, the evaluation needs to be extended to the planning horizon for maximization of the present value of the benefits.

In order to maximize returns over time, the owner of a well will decide on the rate of pumping in every time period such that the present value of the profits is a maximum. Assume that this farmer has a concave revenue function given by $R_t(q_t)$ where q_t is the amount of water pumped in time t and the cost of pumping is given by $C_t(q_t, H_t(X_t))$ where X_t is the cumulative extraction at time t from the aquifer and H_t is the drawdown. The discounted present value (DPV) to a finite time horizon N is given by

$$DPV = \sum_{t=1}^{N} [R_t(q_t) - C_t(q_t - H_t(X_t))] (1 + \gamma)^{-t} \qquad . \quad . \quad . \quad (1)$$

where γ is the assumed discount rate. The maximization of DPV involves finding the q_t^*, the optimal extraction rate at time t. The optimum q_t^* will have the property that $d(DPV)/dq_t = 0$ for every t. In other words, if q_t^* is increased by Δq_t, the increase in present worth of the rent will be equal to the decrease in time period t+1 by reducing q_{t+1}^* by Δq_t. The increase in rent at time t converted to present value is

$$\frac{\left(\frac{dR_t}{dq_t} - \frac{\partial C_t}{\partial q_t}\right) \Delta q_t}{(1 + \gamma)^t}$$

The decrease in rent at t+1 converted to present value is

$$\frac{\left(\frac{dR_{t+1}}{dq_{t+1}} - \frac{\partial C_{t+1}}{\partial q_{t+1}} - \frac{\partial C_{t+1}}{\partial H_{t+1}} \frac{\partial H_{t+1}}{\partial X_{t+1}}\right) \Delta q_t}{(1 + \gamma)^{t+1}}$$

Equating these changes, the optimality condition can be given by

$$(MR_t - MC_t) = (MR_{t+1} - MC_{t+1} - \frac{\partial C_{t+1}}{\partial H_{t+1}} \frac{\partial H_{t+1}}{\partial X_{t+1}}) / (1 + \gamma) \qquad . \quad . \quad . \quad (2)$$

where MR is the marginal revenue and MC is the marginal cost. The last term $(\partial C/\partial H)(\partial H/\partial X)(1+\gamma)^{-1}$ is called the user cost. It represents the value of profits foregone at time t+1 due to the decision to increase pumping by one unit at time t. This decision increases the cumulative extraction, thereby increasing the drawdown and hence the cost at time t+1.

Because an aquifer is a common property serving many users, individuals tend to ignore some of the user costs in their decision-making. Each considers only the cost that is applicable to him, ignoring the cost he imposes on other users by his decision to increase withdrawals. This gives rise to the marginal condition

$$MR_t - MC_t = (MR_{t+1} - MC_{t+1} - \frac{\partial \hat{C}}{\partial H_{t+1}} \frac{\partial H_{t+1}}{\partial X_{t+1}}) / (1 + \gamma) \qquad . \quad . \quad . \quad (3)$$

where the user cost reckoned in the individual's decision is less than that to society, resulting in over-extraction of groundwater. Economists call these non-priced, uncompensated costs "externalities."

Government often acts to protect the public interest by allocating water on the basis of beneficial use up to the point where the average recharge equals the withdrawals. When water withdrawals are large and pumping by one individual imposes costs on others by causing "unreasonable" drawdowns, permits to drill new wells may be denied. The appropriation doctrine, as applied to groundwater, generally tends to be overprotective in that it does not allow for any mining even though it may be in society's interest to do so.

Present surface and groundwater use in Tooele Valley needs to be evaluated in light of anticipated increases in the municipal and agricultural water demands there over the next 30 years. The conjunctive use concept and the effects of externalities need to be included in the analysis. It is likely that a benefit maximization policy could involve some mining. To find the optimal extraction rate, considering water quality and conjunctive use by blending surface and groundwaters of different qualities, a mathematical programming technique was developed.

Tooele Valley is located west of Salt Lake City, Utah, as shown in Figure 1. The valley has a relatively small quantity of good quality surface water which amounts to approximately 30 percent of the estimated annual groundwater recharge (Razem and Steiger 1981). A major portion is already being used for agriculture. The Tooele Valley groundwater system has a single major artesian aquifer which supplies almost all the wells drilled. The quality of groundwater varies significantly over the valley depending on proximity to the recharge area and the amounts of soluble material and the permeabilities of the aquifers. Total dissolved solids in the groundwater range from as low as 400 mg/l to more than 3000 mg/l. The areas with good (0 - 500 mg/l), fair (500 - 1,000 mg/l), and poor (1,000 - 3,000 mg/l) quality waters were identified by Razem and Steiger (1981) and are shown in Chapter III. Because the yields of crops generally decrease with increasing salinity in the irrigation water, water quality is a major factor in the present conjunctive use planning study. Artificial recharge is not considered in the study because of the small amount of surface water available for recharging and the complex hydrogeologic, geochemical, and economical analysis required for its evaluation.

The linear programming optimization model of this study was developed not only to give the crop mix that would maximize net returns, but also to determine whether blending of waters of three different quality levels to produce two more intermediate quality levels for irrigating crops would further increase agricultural returns.

The withdrawals of groundwater of different qualities at different locations as dictated by the optimization model were used as input to the Tooele Valley groundwater simulation model developed by Razem and Bartholoma (1980) to study the resulting drawdowns and their effects on future pumping costs. Large drawdowns affect aquifer storage as well as pumping costs over time, and a dynamic programming scheme to analyze such a situation is briefly described.

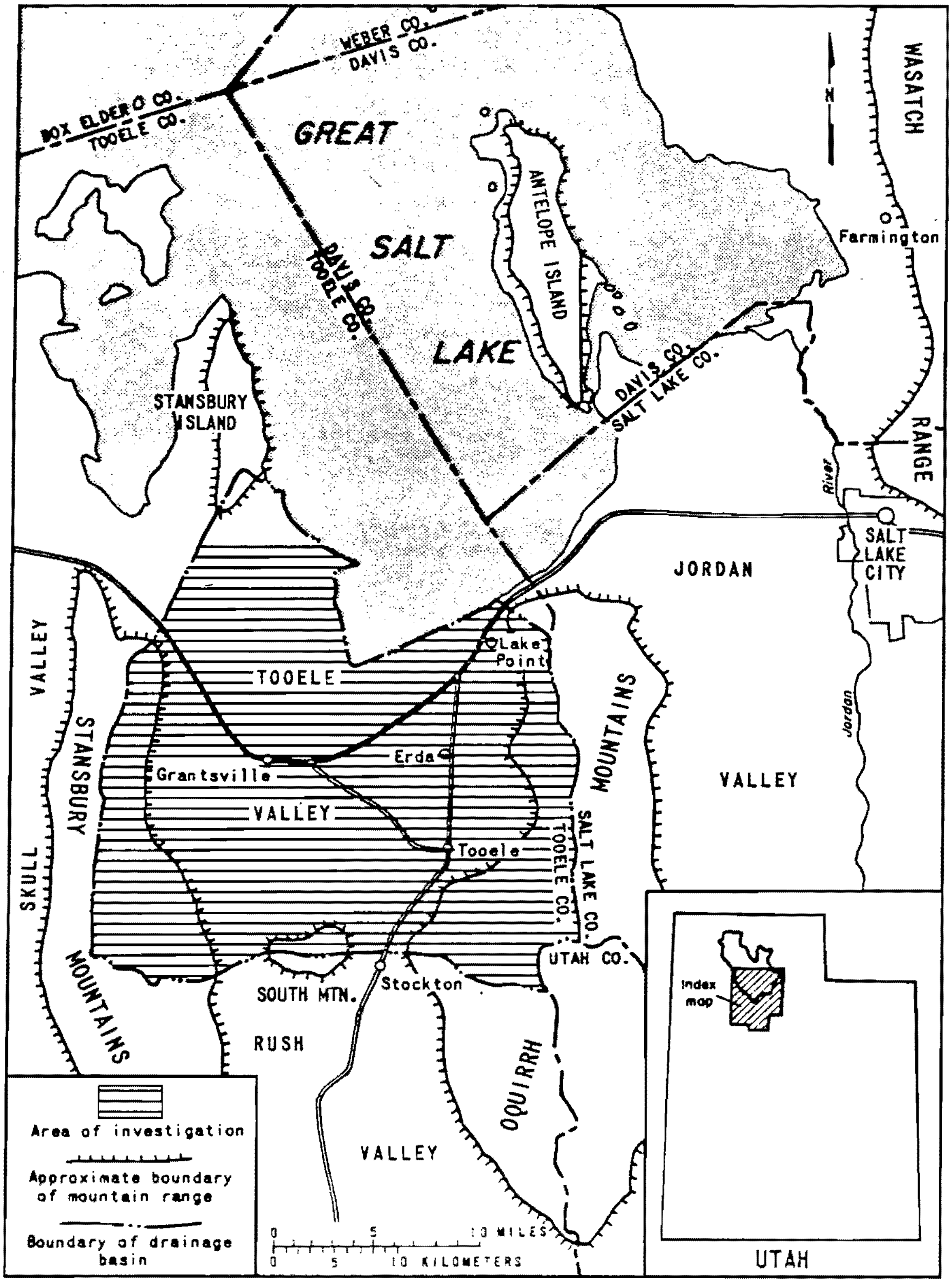


Figure 1. Map of Tooele Valley (from Razem and Steiger 1981).

CHAPTER II

LITERATURE REVIEW

The conjunctive utilization of groundwater reservoirs and surface water facilities is covered in a diverse literature. Qualitative literature describes specific problems in limited geographical areas. These problems involve sea-water intrusion, land subsidence, quantities of groundwater available, artificial recharge, groundwater surface-water conflicts, multisource/multiquality agricultural water use, maximizing food production, etc. This chapter reviews cases where conjunctive water use planning helped solve such problems. It then goes on to discuss the literature available on the engineering, economic, legal and institutional aspects of conjunctive water use planning. Also, some recent literature covers aspects of integrating simulation and optimization models for designing optimal water resource systems.

Mandel (1975) discusses the problem of sea-water intrusion in Tel Aviv, Israel. Greater Tel Aviv is a densely populated area extending over about 100 sq km. Until 1958, its water supply depended solely on local wells exploiting the Pleistocene aquifer. The permissible yield, about 17 x 10^6 m^3/year, was exceeded in the early 1950s and withdrawals reached more than 80 x 10^6 m^3 in 1957/58. A deep cone of depression formed, and sea water intruded to a distance of 2.4 km from the sea coast, putting many wells out of action. A project was initiated to build a temporary fresh-water barrier to check the advance of sea water until the water levels further inland recover sufficiently. Water from the Jordan River was injected into 22 city wells parallel to the shore line and at distances of 1.5 - 3 km east of it. Observations showed that the advance of the sea water was checked during the winter, but during the summer a slow eastward movement was still recognizable.

Garza (1977) studied the feasibility of artificial recharge for subsidence abatement at the NASA-Johnson Space Center in south-eastern Harris County, Texas. The Johnson Space Center was about 13 to 19 feet above mean sea level in 1974 and sinking at a rate of more than 0.2 foot per year. Hydrologic digital models were developed for theoretical determinations of quantities of water needed, under various well-array plans, for artificial recharge of the Chicot and Evangeline aquifers in order to halt the subsidence.

Eastern Washington is experiencing rapid declines in groundwater levels due to irrigation pumping. Feldman, Whittlesey and Butcher (1976) developed a conceptual framework for comparing the economic consequences of the present management policy to avoid exceeding a 10 foot per year decline in the static water level with alternative policies 1) allowing greater decline rates or 2) augmenting the water supply with surface water imported from the Columbia River.

Many stream-aquifer systems have been developed without legal recognition of the hydraulic interrelationships between their groundwater and surface-water components. State of Utah water law does recognize the hydraulic interrelationship between ground and surface water components (personal communication with Barry Saunders, 1983). Although the science of modeling those interrelations has progressed significantly in recent years, little legislation has been passed specifically defining the rights of groundwater and surface-water appropriators from a common stream-aquifer system. Consequently, many such appropriations are on a collision course leading to serious confrontations with the natural system. Bittinger (1980) addresses this as a problem that needs the attention of not only engineers and hydrologists but also lawyers and legislators. He discusses the conflict with examples from Platte River and Frenchman Creek in Nebraska, North Fork Republican River in Colorado, and Solomon River in Kansas.

An economic evaluation of the adjustment alternatives open to irrigated agriculture in the proposed service area of the Central Arizona Project (CAP) in Pinal County, Arizona, is reported by Boster and Martin (1977). The CAP involves construction of an aqueduct to transport water from Lake Havasu on the Colorado River into the Maricopa County-Phoenix area, and then through Pinal County to Tucson. Colorado River water contains different dissolved-salt concentrations than the groundwater and surface water currently being used. Some areas of Pinal County have low salinity ratios, while others have a high salinity ratio; the optimum CAP-local water mix for typical crops was determined through the use of linear programming models. Each model includes alternative crop production activities using various quantities and mixes of CAP water and local surface and groundwater. The models were designed to maximize net farm returns.

Adequate food production is a pressing need in many less developed countries. In Pakistan, the production of food can potentially be increased several times over the present supply. The land resources of the Indus Basin agricultural system far exceed its related water resources. It is, therefore, of paramount importance that the scarce water resources be optimally developed and managed. Chaudhry et al. (1974) discuss an optimal conjunctive use model for the Indus Basin, Pakistan.

Early writers (Kazmann 1951 and Banks 1953), on the subject of joint utilization of surface and groundwater resources, recognized the economic advantages that could be gained from this type of operation. Many physical, engineering, financial, and legal complexities of the problem were delineated. But, only recently have investigators begun to apply optimization methods to develop conjunctive water use plans. An excellent summary of the advantages and disadvantages of the conjunctive use of surface and groundwater reservoirs is presented by Todd (1980).

Engineering Considerations of the Problem

A careful engineering investigation of a river valley is necessary for a conjunctive use management study. Management by conjunctive use requires physical facilities for water distribution, for artificial recharge, and for pumping. Operation requires careful planning to optimize the use of available surface and groundwater resources. The studies require competent personnel, detailed knowledge of the hydrogeology of the basin, records of pumping and recharge rates, and continually updated information on groundwater levels and quality. Data are required on surface water resources, groundwater resources, geologic conditions, the water distribution system, water use, and wastewater disposal. Estimates of future water demands for the area under investigation are also needed.

Digital computer simulation has been used in many conjunctive water use planning studies. Simulation combines theory, data, and programming logic to express, in mathematical terms, the pertinent elements of a complex realworld system (Naylor et al. 1966). Simulation models do not directly provide an optimal solution to a problem. They rather predict the behavior of a system under alternative operation policies, predictions which are essential for determining the optimal policy.

Many digital simulation models are available to investigate the engineering aspects of surface water facilities, groundwater basins, and stream-aquifer interactive systems. A few of them are mentioned below.

Tyson and Weber (1964) used both digital and analog computers to solve the groundwater flow equation. Finite differencing techniques have very often been used to handle partial differential equations on a digital computer. Trescott, Pinder, and Larson (1976) developed a finite-difference two-dimensional groundwater flow simulation model. Trescott and Larson (1976) have written a finite-difference model for simulating three-dimensional groundwater flow. The hydraulics of aquifer flow has also been treated by analytical solutions (Elango et al. 1976), response function and cell models (Schwarz 1976), and finite-element approximations (Willis 1977).

In a recent book, Boonstra and de Riddel (1981) present a groundwater model based on the finite difference method which can be applied to an unconfined aquifer, a semiconfined aquifer, a confined aquifer, or any combination of these. Ahmed (1973) and Daubert (1978) considered the stream-aquifer interaction in their modeling studies. A good discussion of stream-aquifer interaction modeling is available in Morel-Seytoux and Daly (1975).

Economic Studies

A common procedure for formulating a plan for integrated operation of groundwater and surface water systems has been to choose a number of alternative plans, which engineering and economic judgment indicates should be desirable, and then compare the costs and benefits of the alternatives. In this approach, "most economical" is usually loosely defined as "least cost" and may not be an appropriate measure of the best solution in all cases.

Chun, Mitchell, and Mido (1964) follow this approach in studying the conjunctive operation of groundwater basins with surface supplies. They formulated alternative plans representing use of the groundwater basin in coordination with surface facilities in order to meet imposed demands in the system. Economic comparison of alternative plans of operation are made on the basis of converting the annual costs of each alternative into total present worth. The plan chosen as the most economical was the alternative having the least total present worth of future costs. The authors state that, "Because all plans were formulated to satisfy identical physical requirements, the plan with the least total present worth has the greatest benefit/cost ratio."

Renshaw (1963) presents the argument that decisions on the use of groundwater should be based on the long run value of the resource. The economic value of water left in the ground can be estimated by two methods. In the first method, returns are estimated from reduced pumping costs due to reduced mining of groundwater. The second method is based on the capitalized value of water left in storage. Water left in the ground has a greater value than can be obtained from low value uses after pumping. Renshaw's arguments emphasize the value of not pumping groundwater.

Koenig (1963) argues that extractions from groundwater reserves should be viewed in the same manner as extractions from other resource reserves such as oil, coal, or natural gas. Without even considering the replenishment of groundwater reserves, the life of the current reserve of groundwater is more than 18 times the life of any nonreplenishable resource with the exception of bituminous coal. According to Koenig, if the present rate of depletion of groundwater storage is continued, the reserve life would be 7800 years. Alternatives to local shortages of groundwater are reducing use and importing water. The conservative attitude of preventing groundwater mining cannot be justified economically, according to Koenig.

Domenico, Anderson, and Case (1968) present a mathematical expression relating the economic value of groundwater mining to the worth of a basin remaining after the water has been partially depleted. Their expression permits quantification of an optimal storage reserve that may justifiably be exploited. They define sustained yields as use rates determined by and limited to natural replenishment and mining yields as volumes of nonrenewable water in storage independent of the rate of mining. The volume may be mined rapidly or slowly, but it is fixed. Maximization of present worth is taken as the management goal, and the optimization is done by conventional calculus methods.

The patterns of availability, distribution, and consumption of water call for special organizational, administrative, and legal institutions to control its allocation (Gaffney 1969 and Castle and Stoevener 1970). The mobile, flowing nature of the surface resource makes it difficult to establish and maintain the property rights that are the basis for allocation and exchange in a market economy. Furthermore, groundwater provides a well-established example of a natural resource used by many people in common that the market fails to allocate to achieve the maximum net value of production (Ciriacy-Wantrup 1963). Groundwater resources are used by independent pumpers withdrawing from a common pool. Since groundwater moves in response to withdrawals, the action of any one pumper affects resource availability to other users; users are thus interdependent, and external, or spillover, effects occur. The external effects are called "technological diseconomies," technological because the impact is registered through a physical link between production processes, and diseconomies because the effect imposes a cost rather than a benefit to the recipients. When substantial external effects exist, the calculation of benefits and costs by the individual unit fails to reflect the total impact on society, and a misallocation of resources results (Young 1972).

Water resource planners need to consider the interdependency of groundwater pumpers and stream-aquifer interactions. Usually, maximization of net social benefits is the objective of any conjunctive use planning. Optimization techniques are frequently used to define the water resource policy that maximizes the net social benefits.

Optimization Techniques Applied

The concept of optimization implies either maximizing or minimizing some objective function. The objective function might focus on maximization of net benefit or be multiobjective in character. In applying optimization techniques to water resource problems, the guiding principle in selecting the objective function is almost always the allocation of scarce resources. There are many physical, legal, and political constraints or limits on the allocation of water resources, so the problem becomes one of maximizing or minimizing some objective function within those constraints.

The optimization frequently uses linear or dynamic programming. Some advantages and disadvantages of using linear and dynamic programming to optimize water resource systems are reviewed by Chow and Meredith (1969) and Dracup et al. (1972).

The importation of water for irrigated agriculture raises many questions on farm profitability and suggests many adjustment alternatives open to farmers. In particular, how will farmers respond to a new additional water source of differing cost, availability, and quality? Boster and Martin (1979) developed linear programming computer models of representative irrigated farms in Pinal County, Arizona, to project agricultural adjustments to new water from the Central Arizona Project. The models of farm enterprises in Pinal County maximize profits by maximizing net returns above variable production costs. Other applications of LP in conjunctive use include Dracup (1966), Milligan (1970), Boyd (1968), Young (1972), Feldman, Whittlesey and Butcher (1976), and Noel, Gardner and Moore (1980).

Aron (1971) used dynamic programming to develop an optimal policy for operation of a conjunctive use project to meet a forecast demand in the Santa Clara Flood and Water Conservation District. The real system was represented by a simplified model through division into a set of subsystems and flow processes. The internal operation of some of the subsystems were preoptimized independently of each other to reduce the number of decision alternatives considered in the final conjunctive system optimization. The final optimization model consisted of three state and 12 decision variables. An 8-year optimal water-allocation policy was developed in intervals of 3-month periods, based on a stochastic distribution of surface water inflows.

Chaudhry et al. (1974) used dynamic programming with a systematic search algorithm that deleted nonoptimal solutions. They applied it to analyze and optimize the conjunctive use of surface and groundwater resources of the Indus Basin in Pakistan.

Legal and Institutional Aspects of the Problem

Groundwater law needs to define and protect rights to use the water in a way that will protect investment made in groundwater development, facilitate shifts to higher valued uses, and protect the public interest against overuse by individuals who are primarily considering their own welfare. Four legal doctrines (Sato 1962) have been applied in various states at various times. These are:

1. Absolute ownership in which the user has full control of the water underlying his land as long as he does not engage in a use that of itself is harmful to others.

2. Reasonable use in which the user is also constrained within the amounts of water normally needful for his purposes with normal management practices.

3. Correlative rights in which users withdrawing groundwater from a common source are further constrained by the amounts of water available.

4. Appropriate rights in which rights are formalized through an appropriation process administered by a state agency and ordered by date of appropriation in case of shortage.

Groundwater systems respond to geophysical laws controlling recharge, natural discharge, effects of withdrawals by users, and effects of pollution. Since groundwater systems are much slower to respond and more difficult to monitor than are surface flows, extra effort is needed in their management. Because ground and surface waters are physically interconnected and the usage of one affects the other with respect to both quantity and quality, both the laws and management effort should be built from these interrelationships.

The needed overall legal-management framework has been slow to evolve, partially because of uncertainties with respect to these interrelationships as intensified by the unavailability (and cost of obtaining) information on specific situations. However, recent advances in techniques for geotechnical exploration, sophisticated tehniques for modelling the physical system, and operations research techniques for economic optimization, provide the needed tools for studying responses in a stream-aquifer system (Bittinger 1980). They need to be developed and applied in effective legal and institutional management systems.

Because of the inherent interdependency among users of groundwater, intensive exploitation inevitably leads to detrimental external effects. The traditional remedy in the western United States has been to develop additional water supplies by new investments in storage and conveyance (or sometimes recharge) facilities. When supplies of unappropriated water ("free goods" in economic terms) can be developed for a reasonable cost, such construction is justified. However, the traditional large-scale development schemes are becoming increasingly expensive, and institutional changes are needed to give greater emphasis to water resources management and reallocation.

The case for modifying or replacing the present institutions is justified only if the external costs and inefficiencies abated are sufficient to offset both the costs of developing and applying the required information and analytic systems and the added cost of administration. The institutional alternative most commonly advocated is the basin authority. Smith (1964) developed a persuasive argument for moving to management of the entire hydrologic unit to "internalize" the externalities commonly associated with water resource use. Such a basin authority would be designed to balance the benefits and costs among the various types and locations of water use in a river basin.

Integration of Simulation and Optimization Models

As pointed out by Wilkinson and Smith (1975), the process of designing an optimal conjunctive use water resource management system will be more efficient if the simulation model and optimizing routine are seen not as distinct and independent phases, but as complementary and interactive parts of an integrated procedure. The simulation run provides information on the physical response of the system; optimization uses this information in comparing alternatives. Wilkinson and Smith (1975) present an example problem based on studies of the Welland and Nene Rivers in the United Kingdom, illustrating data sets and methods of analysis. The river system embraces a pumped storage reservoir, an artificially recharged aquifer, and several demand centers.

A method to include groundwater variables in linear programming management models was described by Aguado and Remson (1974). Linear algebraic equations obtained from the numerical approximation of the governing groundwater equations are used as constraints in the LP models. The method was used to determine optimal plans for maintaining an excavation site in a dewatered state (Aguado et al. 1974), for disposing of wastewater (Alley et al. 1976), and for exploring an aquifer (Aguado et al. 1977).

Maddock (1974) derived an algebraic technological function (ATF) that relates drawdown to pumping from an unconfined aquifer. Drawdown was estimated with the help of an infinite power series in pumping values, and the ATF is provided by a finite sum of the power series. The ATF can be used as a method of predicting drawdowns from pumping for application in optimization techniques. An application of the ATF for conjunctive use planning is discussed by Haimes (1977). Harl et al. (1971) combined an LP groundwater management model with a river quality simulation model. Other related literature include Elango and Rao (1977), Futagami et al. (1976), and Helweg and Labadie (1977).

CHAPTER III

MODEL FORMULATION FOR THE STUDY AREA

A linear programming (LP) approach was employed to allocate mixed combinations of groundwater and surface water resources of different qualities and costs (due to different pumping lifts) among various crops and municipal demands at a given point in time in the Tooele Valley. The optimal mixing of waters of different qualities was calculated to maximize net returns to fixed inputs in the agricultural sector and benefits to municipal and industrial use. Five different crops (alfalfa, corn silage, dry land wheat, wheat, and barley) were considered. These are the major crops grown in the area.

For this analysis, the valley was divided into three service areas based mainly on existing surface water systems and population centers. The three areas are numbered Location 1 (Grantsville area), Location 2 (Erda area) and Location 3 (Tooele area) and follow boundaries shown in Figure 2. Each location had three different groundwater quality areas (based on TDS); good (0-500 mg/l), fair (500-1000 mg/l), and poor (1000-3000 mg/l). Single samples from representative wells in the valley provided the data to demarcate the good, fair, and poor quality areas. For all practical purposes water quality can be assumed not to vary with time (personal communication with A. C. Razen). Little pockets of groundwater with dissolved solids of greater than 3000 mg/l are neglected in this study. By mixing among both groundwater and surface water, two more intermediate water qualities could be obtained. Thus the LP considered a total of five different water quality levels. The three naturally available quality levels are represented by the subscript ℓ (ℓ = 1, 2, and 3) and the five resultant qualities after mixing are represented by the subscript R (R = 1, 2, 3, 4, and 5). Also, quality levels ℓ = 1, 2, and 3 are the same as quality levels R = 1, 3, and 5. R = 2 and 4 are the two intermediate quality levels.

The Objective Function

Returns from agricultural products are defined as total revenue minus variable production costs. Benefits from public water supply equal the revenue from the sale of water plus the consumer surplus. The objective function is to maximize the sum of the returns from irrigating agricultural crops and benefits from public water supply minus the total cost of supplying water from different sources.

Return from Agricultural Crops

The economic returns from agriculture depend on the crop yields. No soil capability classification was available for Tooele Valley. Some information was obtained by inference from aerial photographs and actual yields of various crops. The soils in the valley are generally homogeneous with respect to agricultural productivity, irrigability, and salinity. For quantitative estimation of the needed properties, the soils were classified as class II according to the land-capability classification described in the Agriculture Handbook No. 210 (Soil Conservation Service, USDA 1973).

Full, as opposed to deficit, irrigation was assumed. If P_j is the

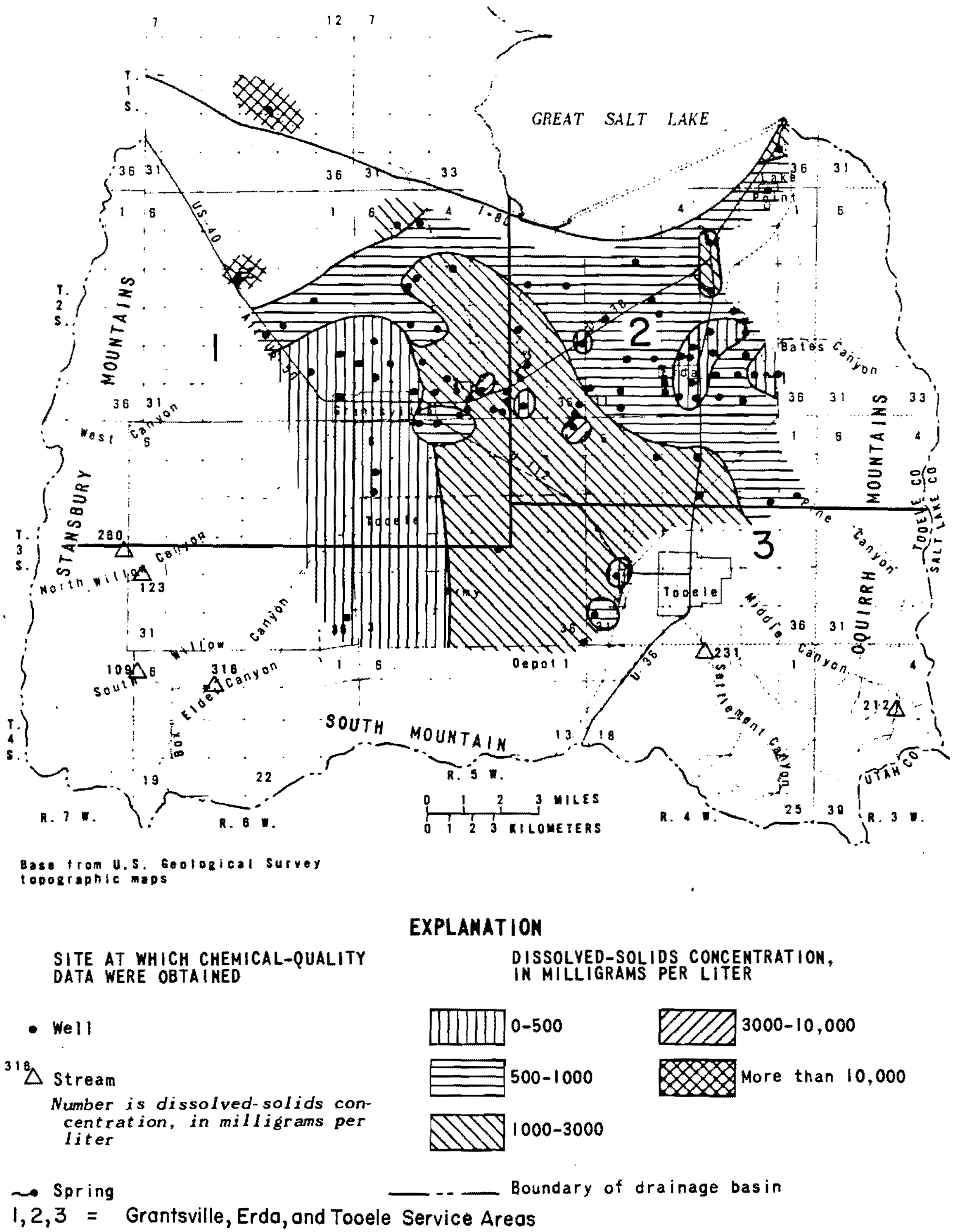


Figure 2. Map of Tooele Valley basin showing the three locations and water quality subareas used in the programming model (adapted from Razem and Steiger 1981).

unit price of the jth crop, L_{ijk} is the acreage of land used for growing the jth crop with kth quality water in location i, and Y_{jk} is the productivity (units of the crop output per acre) of the jth crop when irrigated with kth quality water, then the gross return to agriculture for the entire valley is

$$TR_A = \sum_{i=1}^{3} \sum_{j=1}^{5} \sum_{k=1}^{5} P_j Y_{jk} L_{ijk} \quad . \quad (4)$$

The variable cost associated with growing crop j comes from using various inputs such as seed, fertilizer, labor, and machinery. If C_{jk}^{CUL} is the unit cost (excluding the cost of water) of growing the jth crop with kth quality water per unit of crop output, the total cost of production can be expressed as

$$TC_A = \sum_{i=1}^{3} \sum_{j=1}^{5} \sum_{k=1}^{5} C_{jk}^{CUL} Y_{jk} L_{ijk} \quad . \; . \; . \quad (5)$$

The difference between gross return and total cost yields the returns of agricultural output π_A

$$\pi_A = TR_A - TC_A \quad . \; . \; . \quad (6)$$

Benefit from Public Water Supply

For modeling benefits from public water supply, Q was defined as the quantity of water demanded in acre-feet per year at price P. A linear relationship

$$Q = a + bP \quad . \; . \; . \; . \; . \; . \quad (7)$$

is assumed between Q and P. Constants a and b were estimated with a price elasticity of -0.5 (Hansen and Narayanan 1981)

$$E = -0.5 = \frac{P}{Q} \frac{dQ}{dP} = \frac{P}{Q} \hat{b} \quad . \; . \; . \quad (8)$$

$$\hat{b} = -0.5 \frac{Q}{P} \quad . \; . \; . \quad (9)$$

For Tooele City in the year 1980, Q_o = 4520 ac-ft/yr (208 gpcd) and P_0 = \$166.21 per ac-ft (\$0.38/100 ft^3). Therefore, constants b and a are estimated by $\hat{b}$ and $\hat{a}$ as:

$$\hat{b} = -0.5 \frac{(4520)}{166.21} = -13.6$$

and, $\hat{a}$ = 6780.5

$$Q_0 = 6780.5 - 13.6 P_0 \quad . \; . \quad (10)$$

Dividing Equation 10 by the 1980 population (n_o) of 19,400

$$P_0 = 498.57 - 1426.47 \frac{Q_0}{n_o} \quad . \quad (11)$$

Generalizing Equation 11 to any year t,

$$P_t = 498.57 - 1426.47 \frac{Q_t}{n_t} \quad . \quad (12)$$

Total benefit realized from public water supply is obtained by integrating Equation 12 with respect to Q_t as

$$\pi_{PS_t} = \int P_t \, dQ_t$$

$$= \int \left(498.57 - 1426.47 \frac{Q_t}{n_t}\right) dQ_t$$

$$\pi_{PS_t} = 498.57 \, Q_t - 713.24 \frac{Q_t^2}{n_t} \quad (13)$$

Water Cost

Water cost is the sum of surface water cost and groundwater cost. Let C^{NDSW} be the average cost of newly developed surface water per acre-foot and C^{PDSW} be the variable cost of presently developed surface water per acre-foot. Let $SWNP_{i\ell}$ be the average annual amount of newly developed surface water in location i of quality ℓ. $PDSW_{i\ell}$ is the average annual amount of presently developed surface water of quality ℓ in location i, and $SWNM_{i\ell}$ is the average annual surplus amount of water that is not used from the reservoir of already developed surface water in location i and quality ℓ. Therefore, total surface water costs are represented as

$$TSWC = C^{NDSW} \left(\sum_{i=1}^{3} \sum_{\ell=1}^{3} SWNP_{i\ell} \right) + C^{PDSW} \left(\sum_{i=1}^{3} \sum_{\ell=1}^{3} PDSW_{i\ell} - \sum_{i=1}^{3} \sum_{\ell=1}^{3} SWNM_{i\ell} \right) \quad . . . \quad (14)$$

Let $MVCE_{i\ell}$ be the weighted annual marginal variable cost of existing well capacity in location i of quality ℓ in dollars/year/gpm/well. An example computation is presented in Chapter IV. Let $NEPW_{i\ell}$ be the number of existing wells in location i of quality ℓ. Let $QEP_{i\ell}$ be the average capacity of the ℓth quality water wells used in location i in gpm. Let $TAC_{i\ell}$ be the total annual cost of a new well of given capacity (400 gpm in this study) in dollars/year/well of ℓth quality water in location i. Let $NNW_{i\ell}$ be the number of new ℓth quality water wells in ith location. Thus, the total groundwater cost was estimated as

$$TGWC = NEPW_{i\ell}\ MVCE_{i\ell}\ QEP_{i\ell} + NNW_{i\ell}\ TAC_{i\ell} \quad . . . . \quad (15)$$

Land Conversion Cost

The land that is not presently irrigated but potentially irrigable would require costs in preparing for irrigated agriculture. Let this cost be C^{LC} dollars/acre. Let $PTIL_{ijk}$ be the potentially irrigable land (in acres) used for irrigated crop j with water quality k in ith location. Then, total cost of land conversion is given by

$$TCLC = \left(\sum_{i=1}^{3} \sum_{j=1}^{5} \sum_{k=1}^{5} PTIL_{ijk} \right) C^{LC}. \quad (16)$$

Overall Objective Function

The objective function can now be written as:

$$\begin{aligned} \text{Max } Z &= \pi_A + \pi_{PS} - TSWC - TGWC - TCLC \\ &= \sum_{j=1}^{5} \sum_{k=1}^{5} \left[(P_j - C_{jk}^{CUL})\, Y_{jk} \left(\sum_{i=1}^{3} PIL_{ijk} + \sum_{i=1}^{3} PTIL_{ijk} \right) \right] \\ &+ \sum_{i=1}^{3} \left[498.57\, Q_{it} - 713.24 \frac{Q_{it}^2}{n_{it}} \right] \\ &- C^{SWNP} \left(\sum_{i=1}^{3} \sum_{\ell=1}^{3} SWNP_{i\ell} \right) \\ &- C^{PDSW} \left(\sum_{i} \sum_{\ell} PDSW_{i\ell} - \sum_{i} \sum_{\ell} SWNM_{i\ell} \right) \\ &- NEPW_{i\ell}\ MVCE_{i\ell}\ (QEP_{i\ell}) \\ &- NNW_{i\ell}\,(TAC_{i\ell}) - \left(\sum_{i} \sum_{j} \sum_{k} PTIL_{ijk} \right) \\ &C^{LC} \quad . . . . \quad (17) \end{aligned}$$

Basic Constraints

Agricultural Production

Land. The land available for cultivation in each location could either be presently irrigated land (PIL) or potentially irrigable land (PTIL). Acreage of presently irrigated land used for all crops cannot exceed the total presently irrigated land in each location (PIL_i^*).

$$\sum_{j=1}^{5} \sum_{k=1}^{5} PIL_{ijk} \leq PIL_i^*$$

$$i = 1, 2, 3 \quad . \; . \; . \quad (18)$$

Similarly, acreage of potentially irrigable land used for all crops cannot exceed the total potentially irrigable land in each location ($PTIL_i^*$)

$$\sum_{j=1}^{5} \sum_{k=1}^{5} PTIL_{ijk} \leq PTIL_i^*$$

$$i = 1, 2, 3 \quad . \; . \; . \quad (19)$$

Crop rotation. Crop rotation is required for diversification purposes and to maintain the quality of soil. A dynamic model would be required to replicate rotations, but the results can be represented in a static model by specifying a mix of crops one would expect to result in a given year from following a rotation. The specific rotational constraints used in this study of Tooele Valley basin are written in terms of acreage for each location as:

5 Irrigated Wheat + 5 Barley $\geq$ Alfalfa

8 Corn Silage $\leq$ Alfalfa + Wheat + Barley

Alfalfa $\geq$ Barley . . . . . . (20)

These constraints were derived from Anderson et al. (1973) and consultation with the Department of Plant Science, Utah State University.

Water Requirements and Availabilities

Water requirement for agriculture. Let ϕ_j be the consumptive use per acre required by crop j with full irrigation. Let α be the irrigation efficiency. The amount of water required from the source for crop j (CWR_j) is then given by ϕ_j/α. If WUA_{ik} is the kth quality water used for agriculture in ith location,

$$\sum_{j=1}^{5} (CWR_j)(PIL_{ijk} + PTIL_{ijk}) - WUA_{ik} = 0$$

$$i = 1,2,3$$
$$k = 1,2,3,4 \text{ and } 5$$

$$. \; . \; . \quad (21)$$

Water availabilities. Total surface water used of ℓth quality in ith location ($SWUT_{i\ell}$) cannot exceed the amount of water of that quality available in that location ($SWUT_{i\ell}^*$).

$$SWUT_{i\ell} \leq SWUT_{i\ell}^* \quad . \; . \; . \quad (22)$$

$$i = 1, 2, 3$$
$$\ell = 1, 2, 3$$

$SWUT_{i\ell}$ includes any water used for blending to obtain two other intermediate quality waters. Groundwater withdrawals from existing pumping wells cannot exceed the maximum well capacity ($QEP_{i\ell}^*$).

$$QEP_{i\ell} \leq QEP_{i\ell}^* \quad . \; . \; . \quad (23)$$

Usable discharge from existing flowing wells cannot exceed the total discharge during irrigation season ($UDFW_{i\ell}^*$).

$$UDFW_{i\ell} \leq UDFW_{i\ell}^* \quad . \; . \; . \quad (24)$$

It was assumed that each new well drilled will be of 400 gpm capacity. A limitation in number of wells drilled in a given quality subarea within each location can be incorporated. The annual ℓth quality groundwater withdrawal in ith location ($GWUT_{i\ell}$) is represented as

$$UDFW_{i\ell} + (Kt_m)\ QEP_{i\ell}\ NEPW_{i\ell} + NNW_{i\ell}\ (\hat{Q}_c) = GWUT_{i\ell} \quad . \quad (25)$$

where K is the factor of conversion from gallons to acre-feet and t_m is the total pumping period in a year expressed in minutes. An upper limit on the annual groundwater withdrawal from the basin can also be incorporated.

Blending and Water Quality

Figure 3 shows alternatives of blending three different quality waters available in the basin to obtain two more intermediate qualities in each of the three locations. $SWUB_{i\ell k}$ represents amount of ℓth quality surface water in ith location used for blending to produce kth quality agricultural water. $GWUB_{i\ell k}$ represents amount of ℓth quality groundwater in ith location used for blending to produce kth quality agricultural water. The water provided for public supply is assumed to be of good quality only (0-500 mg/l) and hence no blending could be used. Also, for this study, it is assumed that there is no transfer of water from one location to the other. All the necessary blending and transport of water is limited within each location.

The following five constraints for each location say that the water used for agriculture and public supply of a given quality (WUA_{ik} and PSW_i) is equal to the sum of waters of different sources and qualities used in blending to produce the water of that quality.

$$SWUB_{i11} + GWUB_{i11} - WUA_{i1} - PSW_i = 0$$

$$SWUB_{i12} + GWUB_{i12} + GWUB_{i22} + GWUB_{i32} - WUA_{i2} = 0$$

$$SWUB_{i13} + GWUB_{i13} + GWUB_{i23} + GWUB_{i33} - WUA_{i3} = 0$$

$$SWUB_{i14} + GWUB_{i14} + GWUB_{i24} + GWUB_{i34} - WUA_{i4} = 0$$

$$GWUB_{i35} - WUA_{i5} = 0$$

$$i = 1,2,3 \quad . \quad . \quad (26)$$

The next four constraints say that the total amount of water of a given quality and source used is equal to the sum of waters of the given quality and source used in blending various qualities of water in each location.

$$SWUB_{i11} + SWUB_{i12} + SWUB_{i13} + SWUB_{i14} - SWUT_{i1} = 0$$

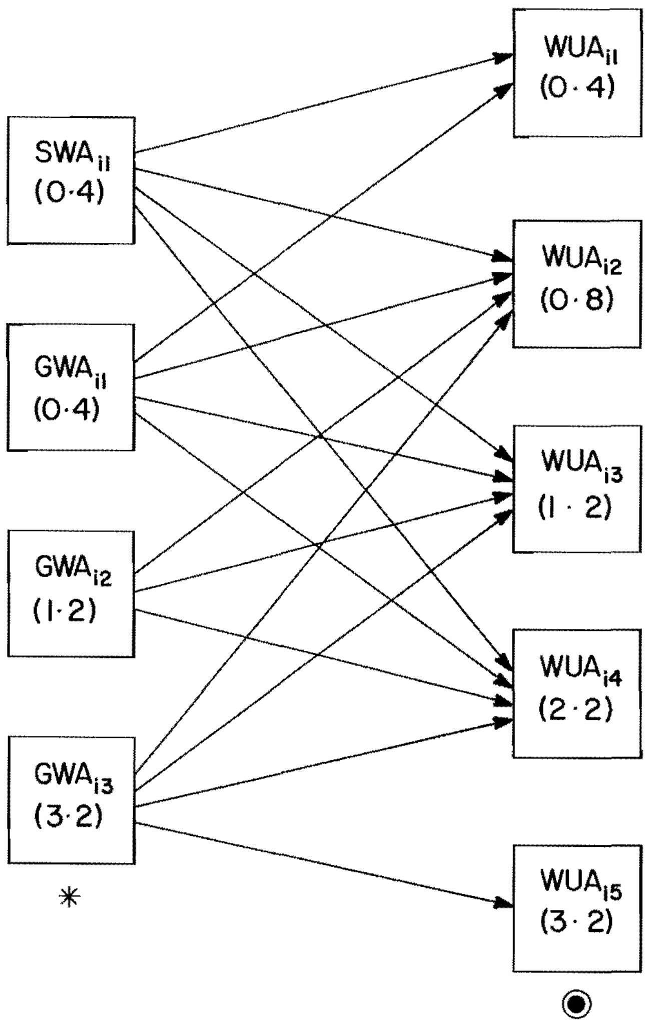
$$GWUB_{i11} + GWUB_{i12} + GWUB_{i13} + GWUB_{i14} - GWUT_{i1} = 0$$

$$GWUB_{i22} + GWUB_{i23} + GWUB_{i24} - GWUT_{i2} = 0$$

$$GWUB_{i32} + GWUB_{i33} + GWUB_{i34} + GWUB_{i35} - GWUT_{i3} = 0$$

$$i = 1,2,3 \quad . \quad . \quad (27)$$

Another five constraints for each location are necessary for maintaining mass balance of salt during blending. These constraints simply state that the total amount of salt in mixing water should be equal to the salt in the resultant water. These constraints are developed by multiplying each variable in constraint set 26 with the corresponding salt concentration in tons/



EXPLANATION

SWA_{ik} = Available surface water of kth quality in ith location (i = 1, 2, 3 k = 1, 2, 3)

GWA_{ik} = Available groundwater of kth quality in ith location (i = 1, 2, 3 k = 1, 2, 3)

WUA_{il} = Water used for Agriculture of lth quality in ith location (i=1,2,3 l=1,2,3,4,5)

$SWUB_{ikl}$ = Surface water of kth quality in ith location used for blending to produce lth quality water

$GWUB_{ikl}$ = Groundwater of kth quality in ith location used for blending to produce lth quality water

* note: All surface water is of good quality, groundwater may be of good, fair or poor quality (electrical conductivity being 0·4, 1·2 and 3·2 mmhos cm^{-1} respectively, which are given within parenthesis)

◉ note: Water is used for agriculture in five different qualities which includes two additional and intermediate qualities

Figure 3. Combinations for mixing three different qualities of water available as groundwater and surface water for producing two additional, intermediate qualities.

acre-foot. These are represented as

$$0.3163\ SWUB_{i11} + 0.3163\ GWUB_{i11} - 0.3163\ WUA_{i1} - 0.3163\ PSW_i = 0$$

$$0.3163\ SWUB_{i12} + 0.3163\ GWUB_{i12} + 0.9492\ GWUB_{122} + 2.5313\ GWUB_{i32} - 0.6328\ WUA_{i2} = 0$$

$$0.3163\ SWUB_{i13} + 0.3163\ GWUB_{i13} + 0.9492\ GWUB_{i23} + 2.5313\ GWUB_{i33} - 0.9492\ WUA_{i3} = 0$$

$$0.3163\ SWUB_{i14} + 0.3163\ GWUB_{i14} + 0.9492\ GWUB_{i24} + 2.5313\ GWUB_{i34} - 1.7403\ WUA_{i4} = 0$$

$$2.5313\ GWUB_{i35} - 2.5313\ WUA_{i5} = 0$$

$$i = 1,2,3 \quad . \; . \; . \; . \; . \; . \quad (28)$$

The linear programming model described in this chapter gives the crop mix that would maximize net agricultural returns. It decides whether blending of waters of three different quality levels to produce two more intermediate quality levels for irrigating crops would increase net benefits. Sources of water to use and amounts to be used for blending are also indicated.

Intertemporal Decisions for Groundwater

Using pumping costs based on the drawdowns at the beginning, the solution to the linear programming model (LP1) will give the groundwater withdrawals for the first 5-year period. These withdrawals will be input to the two dimensional finite-difference aquifer simulation model (ASM) (Trescott, Pinder and Larson 1976). The drawdowns at the end of the first 5-year period are obtained from the ASM. Changes in water quality with depth (if any) were not considered or simulated.

Let the optimal groundwater withdrawal for the first 5-year period obtained from the LP1 model for this period be q_1^*. There is a net benefit corresponding to this solution, π_1^*. The value of q_1^* is supplied to the ASM to predict the drawdown for the beginning of the second period. This drawdown is used to calculate the pumping costs for the second period model LP2. The process can be repeated for all the 5 year periods to determine q_1^*, q_2^*, q_3^*, q_4^*, q_5^*, and q_6^* and the corresponding optimal net benefits, π_1^*, π_2^*, π_3^*, π_4^*, π_5^*, and π_6^*. At the end of the 30 year horizon, if we sum up the six separate optimal net benefits corresponding to six different 5-year periods, the total discounted benefit over the 30 year horizon may be obtained. This may not be the maximum that we could have achieved because no provision is made for management to require users to reduce usage to take into account costs inflicted on other users (the common property resource problem). A 30-year planning period is assumed so that present value of benefits occurring at the end of the planning period is less and doesn't effect the present decisions significantly. Also, there is uncertainty of parameters involved in choosing greater planning horizons.

Dynamic Programming

In order to take into account the user cost and find the optimal withdrawals, the following dynamic programming scheme is proposed. Given the initial conditions, the cost of pumping is calculated and input in LP1. The first period model LP1 is parametrically solved for various levels of total groundwater withdrawal q_1^i ($i = 1, 2, \ldots n_1$), by changing the right hand side of the constraint corresponding to total groundwater withdrawal. Let $q_1^{n_1}$ be the maximum possible withdrawal as constrained by well capacity, aquifer characteristics or total groundwater stock in time period 1. Define the cumulative withdrawal from the aquifer over the 5 years of the first period as X_1^i. For time period 1, set $X_1^i = q_1^i$. The values for the net benefit $\pi_1^i(X_1^i) = \pi_1^i(q_1^i)$ can be found. For each q_1^i ($i = 1, 2, \ldots n_1$), run the aquifer simulation model (ASM) and predict the drawdown and consequent unit pumping cost c_2^i for the second period LP2 model. For each c_2^j ($j = 1, 2, \ldots n_1$), run LP2 parametrically for different $q_2^i = (X_2^i - X_1^j)$, $X_2^i - X_1^j > 0$, $j = 1, 2, \ldots n_1$), by changing the right hand side of the groundwater constraint in LP2. Let the net benefit be $\pi_2(X_2^i - X_1^j)$. By using the forward recurrence relationship of dynamic programming (DP)

$$Z_{t+1}(X_{t+1}) = \max_{\substack{0 \leq X_t \leq X_t^* \\ X_t \leq X^{t+1}}} \left\{ Z_t(X_t) + \frac{1}{(1+\gamma)^t} \pi_{t+1}(X_{t+1} - X_t) \right\}$$

$$0 \leq X^{t+1} \leq X_t^* + R_{t+1} \qquad \ldots \quad (29)$$

where Z_{t+1} is discounted present value up to $t+1$, X_t^* is the maximum cumulative extraction at time t, (given by $q_t^{n_t}$) and R_{t+1} is the net recharge rate at $t+1$ and is exogenous to the model. For tabular form, the relationship is given by:

$$Z_{t+1}(X_{t+1}^i) = \max_{\substack{j=1,2\ldots n_t \\ j \leq i}} \left\{ Z_t(X_t^j) + \frac{1}{(1+\gamma)^t} \pi_{t+1}(X_{t+1}^i - X_t^j) \right\}$$

$$i = 1, 2 \ldots n_{t+1} \qquad \ldots \quad (30)$$

The optimal values of the state variables $\hat{X}_t$ can be found for any finite time horizon $t = 1, 2, \ldots N$. The differences between successive $\hat{X}_t$ gives the rates of extractions

$$q_{t+1}^* = \hat{X}_{t+1} - \hat{X}_t, \quad t = 1, 2 \ldots N-1 \qquad \ldots \quad (31)$$

The proposed dynamic programming approach requires running the simulation model (ASM) one period at a time for N (Σn_i) times. It requires $\sum_{i=1}^{N} n_i(n_i + 1)/2$ solutions of the LP models. Although these numbers appear to be staggering, the procedure can be programmed for the computer, and optimal solutions can be obtained at reasonable costs.

There are certain important assumptions implicit in the procedure outlined here. The time-interval of a period is to be chosen in such a way as not to have transient responses of pumping in any time period carried over to subsequent time periods, or in other words, a steady state is reached before the beginning of next time period. If this were not so, then the principle of optimality breaks down and the application of dynamic programming (DP) is invalid. Another important assumption is that the unit cost of extraction remains constant throughout a time period irrespective of the amount of extraction. This cost depends only on the value of the state variable at the end of the previous time period. Well interference effects in the concurrent time period are also assumed negligible. Theoretically, the last two assumptions could be relaxed and the algorithm reworked with additional effort.

Figures 4 and 5 show the schematics of water allocation under externality and through the dynamic optimization scheme respectively.

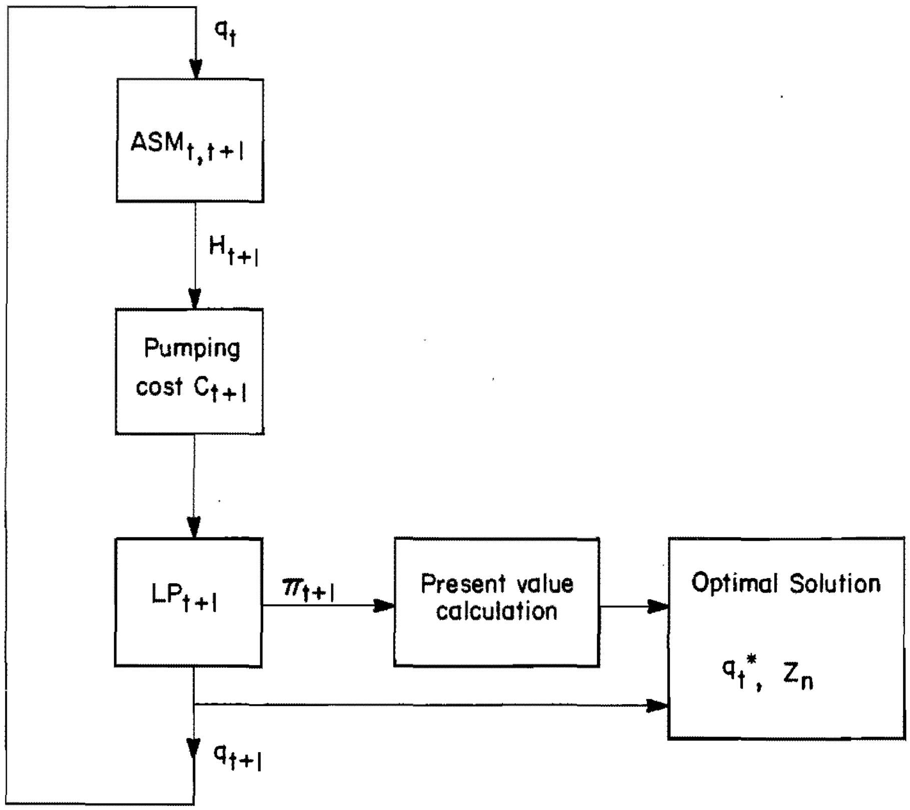


Figure 4. Schematic of water allocation under externality.

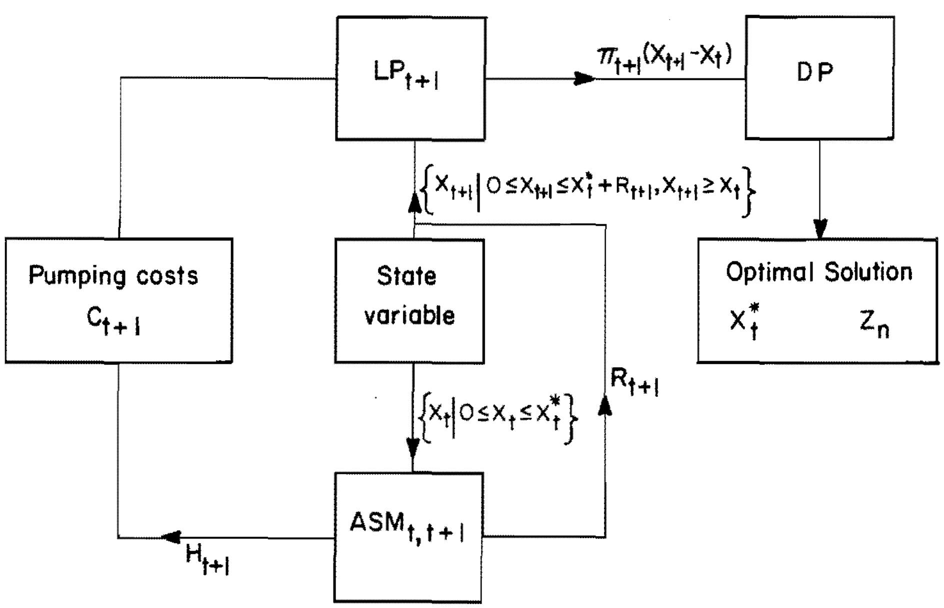


Figure 5. Schematic of dynamic optimization scheme.

CHAPTER IV

DATA DEVELOPMENT

Crop Productivity

Crop productivity data with full irrigation with high quality water in Tooele Valley were obtained for land class II from Keith et al. (1978). Productivity decreases with increasing salt content of irrigation water. Based on the linear relationship between crop yield and salinity of the irrigation water proposed by Maas and Hoffman (1976), Ayers and Westcot (1976) developed a crop-tolerance table. Their major assumptions were that 1) the leaching fraction is in the range of 15-20 percent, 2) the average salinity of soil water taken up by crop is about three times that of irrigation water applied, 3) the average salinity of soil water taken up by crop is about two times that of the soil saturation extract, 4) the crop yields are closely related to the average salinity of the root zone, and 5) the water uptake is normally much higher from the upper root zone as assumed with the 40-30-20-10 percent relationship, which says that 40 percent of soil moisture extraction by roots takes place in the top 25 percent of the root depth, 30 percent of soil moisture extraction in the next 25 percent of the root depth, etc. This crop-tolerance table was used to calculate crop yields at five different water quality levels used in this study with the results given in Table 1.

Crop Water Requirements

Crop water requirement is the crop consumptive use divided by the irrigation efficiency. An overall irrigation efficiency of 0.60 was assumed for Tooele Valley where approximately a third of the area is flood irrigated and the remainder is sprinkler irrigated (Tooele County Extension Office). This value was applied to compute crop water requirements in this study. Crop consumptive use data were obtained from

Table 1. Productivity per acre of various crops in Tooele Valley for land class II at five different irrigation water quality levels.

Crop		Full Yield	Quality 1	Quality 2	Quality 3	Quality 4	Quality 5
Alfalfa[a]	Tons	4.03	4.03	4.03	4.03	3.63	3.22
Corn Silage[a]	Tons	19.36	19.36	19.36	19.36	17.23	14.9
Dry Wheat[b]	Bushels	24.7	-	-	-	-	-
Wheat[b]	Bushels	40.0	40.0	40.0	40.0	40.0	40.0
Barley[a]	Bushels	73.89	73.89	73.89	73.89	73.89	73.89

[a]Keith et al. (1978)
[b]Department of Agriculture (1980)

Table 2. Crop water requirements by crops in ac-ft/acre in Utah.

Crop	Consumptive Use	Source of Data	Crop Water Requirement
Alfalfa	2.0	Keith et al. (1978)	3.33
Corn Silage	1.30	Keith et al. (1978)	2.17
Wheat	1.67	Narayanan et al. (1979)	2.78
Barley	1.20	Keith et al. (1978)	2.00

Keith et al. (1978) and Narayanan et al. (1979). Table 2 gives the data used.

Crop Prices

Crop prices were taken from Narayanan et al. (1979), Keith et al. (1978), Department of Agriculture, State of Utah (1980), and USDA (1981). All prices were reduced to 1980 dollars using index of prices received by farmers reported by the Crop Reporting Board (USDA, March 1980) with the results in Table 3.

Cost of Preparing Potentially Irrigable Land for Irrigation

The preparation of land for irrigation requires costs for land development and installation of an on-farm water distribution system. The costs for Tooele Valley region for land class I were obtained from Keith et al. (1978). This cost estimate was updated to 1980 costs using Water and Power Construction Cost Index from the Engineering News Record. The 1980 annual cost was $21.89 per acre for irrigated cultivation and $19.70 for dry farm cultivation.

Whenever potentially cultivable land is used for cultivation, the above cost was substracted from the revenue accruing per acre of new land developed.

Table 3. 1980 crop prices (dollars per unit) in Utah.

Crop	Price in Dollars Per Unit
Alfalfa	$56.88/Ton
Corn Silage	$16.68/Ton
Wheat	$ 3.49/Bushel
Barley	$ 2.33/Bushel

Cost of Cultivation of Crops Excluding Water Cost

Cost of cultivating crops in dollars per acre in land class II in Tooele Valley area was obtained from Keith et al. (1978) and updated to 1980 dollars using production indices reported in Agricultural Prices (USDA 1980). The costs were then converted to dollars/unit of crop. Since crop yield varies with water quality, the cost of cultivation in dollars/unit of crop increases with a reduced yield. Table 4 gives the data for cost of cultivation for various crops grown with different quality waters.

Surface Water Costs

Per acre foot surface water costs for agriculture and public supply activities such as diversions, transportation, storage, present and new distribution, etc., were obtained from King et al. (1972) and updated to 1980 using Water and Power Construction Index

Table 4. Cost of cultivation of crops excluding cost of water.

Crop	Water Quality[b]	Cultivation Cost $/Acre	Cultivation Cost $/Unit of Crop
Alfalfa	1	$134.83	$33.45/Ton
	2		$33.45/Ton
	3		$33.45/Ton
	4		$37.14/Ton
	5		$41.87/Ton
Corn Silage	1	$180.00	$ 9.30/Ton
	2		$ 9.30/Ton
	3		$ 9.30/Ton
	4		$10.45/Ton
	5		$12.08/Ton
Dry Wheat[a]	-	$ 53.03	$ 2.15/Bushel
Wheat	1	$ 70.00	$ 1.75/Bushel
	2		$ 1.75/Bushel
	3		$ 1.75/Bushel
	4		$ 1.75/Bushel
	5		$ 1.75/Bushel
Barley	1	$ 91.64	$ 1.24/Bushel
	2		$ 1.24/Bushel
	3		$ 1.24/Bushel
	4		$ 1.24/Bushel
	5		$ 1.24/Bushel

[a]Cost corresponds to land class IV.
[b]1 is the highest quality water.

from Engineering News Record (1980). Estimated cost of presently developed local surface water was $2.54/acre foot and of newly developed water was $17.63/acre foot.

Cost of Electrical Energy for Irrigation Pumping

Monthly pumping costs were estimated for four different wells in Tooele Valley for 24 hours per day pumping throughout the irrigation season from May 25 to September 15. The yields of the wells ranged from 120 gpm to 1700 gpm. The lifts varied between 45.5 feet and 166.1 feet. An overall pumping plant efficiency of 0.517 was used (Wright et al. 1976). Monthly bills were calculated (Table 5) based on the 1980 rate structure for irrigation and soil drainage pumping power service by the Utah Power and Light Company. The energy costs for the four wells varied from 4.21 to 5.12 per kwh, and an average of 4.78 per kwh was subsequently used in computing groundwater pumping costs.

Cost of Pumping from Existing Wells

Only variable or production costs were considered for the existing wells. These are costs associated with the

Table 5. Cost estimates of electrical energy for irrigation pumping in Tooele Valley based on four typical wells.

Well Number	Depth to Water Table in Feet[a]	Yield (gpm)[a]	Power (kw)	Total Energy for the Season (kwh)	Monthly bill in dollars					Total Season Bill	Average Cost of Energy in ¢/kwh
					May	June	July	August	September		
(C-2-4) 33 dac-1	55.8 (3-27-78)[b]	120 (7-18-78)[b]	2.44	6,676	35.41	83.33	85.41	85.41	52.07	341.63	5.12
(C-2-4) 34 adc-1	98.0 (3-18-70)[b]	480 (7-13-78)[b]	17.16	46,950	270.49	541.97	552.90	552.90	377.98	2,296.24	4.89
(C-2-5) 36 dcd-1	45.5 (3-14-62)[b]	1000 (7-14-78)[b]	16.60	45,418	261.54	525.66	536.24	536.24	367.02	2,226.70	4.90
(C-3-6) 1 bdb-1	166.1 (3-15-78)[b]	1700 (7-5-78)[b]	103.00	281,808	1,526.61	2,747.09	2,798.12	2,798.12	1,981.01	11,850.95	4.21

[a]Data from Razem and Steiger (1981)
[b]Date of measurement

Average energy costs = 4.78 ¢/kwh

normal operation of groundwater pumpage. The principal items are energy cost, operation cost, and maintenance and service costs.

The variable cost in dollars per year for an electric pumping plant of less than 150 horsepower was given in terms of pumpage parameters by Nuzman (1967) as

$$VC = 1.886 \times 10^{-6}\ C_k\, QH\ t_h/E_f + 0.0607\ Q^{0.47}\ H^{0.26}\ t_h^{\ 0.34} + 0.475\ Q^{0.84}\ H^{0.40} \quad . \quad . \quad (32)$$

where C_k is the cost of electrical energy in cents per kilowatt-hour (4.78 /kwh); Q is the pump discharge in gallons per minute; H is the total head in feet; t_h is the season operating time in hours (2736 hrs); and E_f is the overall efficiency of conversion of electrical energy to mechanical work expressed as a decimal (0.517). The first term estimates the energy cost, and the second and third terms are for operation and maintenance (after Eyer 1965), respectively.

The coefficients of the operation and maintenance terms in Equation 32 needed to be adjusted to reflect the 1980 wage rates for pumping plant operators and mechanics. A wage rate of \$5.00/hour for pumping plant operators and a wage rate of \$8.00/hour for mechanics was obtained from Utah State University Engineer's Office. The coefficients for the operation and maintenance terms were then revised with the results shown in Equation 33 in 1980 dollars.

$$VC = 1.886 \times 10^{-6}\ C_k\, QH\ t_h/E_f + 0.1540\ Q^{0.47}\ H^{0.26}\ t_h^{\ 0.34} + 0.1640\ Q^{0.84}\ H^{0.40} \quad . \quad . \quad (33)$$

Taking derivatives of both sides of Equation 33 with respect to pump discharge Q (gpm) gives the marginal variable costs of pumping from existing wells (MVCE) in dollars/year/plant/gpm.

$$\frac{d(VC)}{d(Q)} = MVCE = 1.886 \times 10^{-6}\ C_k\ H\ t_h/E_f + 0.0724\ Q^{-0.53}\ H^{0.26}\ t_h^{\ 0.34} + 0.1378\ Q^{-0.16}\ H^{0.40} \quad . \quad . \quad (34)$$

For each groundwater quality subarea in each of the three locations, an average value for Q ($QEP_{i\ell}*$), H ($H_{i\ell}$) and depth of well ($D_{i\ell}$) was determined from available data as given in Appendix A. $D_{i\ell}$ is later used for calculating the construction cost of a new well.

Using the average H and for each Q, MVCE was computed. For example, good quality subarea in location 1 has an average H = 57.5'. For Q = 760,

$$\begin{aligned} MVCE &= 1.886 \times 10^{-6} \times (4.78) \times 57.5 \\ &\times 2736/0.517 + 0.0724 \\ &\times (760)^{-0.53} \times (57.5)^{0.26} \\ &\times (2736)^{0.34} + 0.1378 \\ &\times (760)^{-0.16} \times (57.5)^{0.40} \\ &= 2.74 + 0.09 + 0.24 \\ &= \$3.07/year/plant/gpm \end{aligned}$$

Similarly for Q = 750, MVCE = 3.07 and for Q = 1200, MVCE = 3.03.

A weighted marginal variable cost for the subarea ($MVCE_{11}$) was calculated as explained in Table 6.

Table 6. Computing weighted marginal variable cost of pumping from existing wells (location 1, good quality subarea).

Q (gpm)	Number of Wells	MVCE $/year/well/gpm	Weighted MVCE $/year/well/gpm
760	1	3.07	1/3 x (3.07)
750	1	3.07	1/3 x (3.07)
1200	1	3.03	1/3 x (3.03)

$MVCE_{11}$ = 1/3 x (7.07) + 1/3 (3.07) + 1/3 (3.03) = $3.06/year/well/gpm

Using similar procedures, $MVCE_{i\ell}$ were calculated for ℓ = 1, 2, 3 and i = 1, 2, 3. Values are tabulated in Table 7.

The amount of existing pump capacity to use in each quality subarea in every location ($QEP_{i\ell}$) was a decision variable in the LP model such that $QEP_{i\ell} \leq QEP_{i\ell}^*$. If the number of existing wells in the corresponding subarea is $NEPW_{i\ell}$, total cost of pumping from existing wells in that subarea is $NEPW_{i\ell} \times MVCE_{i\ell} \times QEP_{i\ell}$. The total groundwater pumped from existing wells in the subarea is then equal to $K \times t_m \times QEP_{i\ell} \times NEPW_{i\ell}$, where K is the factor of conversion from gallons to acre-feet (3.0684×10^{-6}), and t_m = total pumping time during the year in minutes (1,64,160).

Construction, Operation, and Maintenance Costs of a New Well

Both fixed costs and variable costs are to be considered in the development

Table 7. Weighted marginal variable cost of pumping from existing wells in each quality subarea in each location.

Location (i)	Quality Subarea (ℓ)	$MVCE_{i\ell}$ $/well/year/gpm
1	Good (1)	3.06
1	Fair (2)	1.34
1	Poor (3)	1.22
2	Good (1)	2.09
2	Fair (2)	3.12
2	Poor (3)	0.94
3	Good (1)	18.34
3	Fair (2)	21.32
3	Poor (3)	16.33

of a new well. For this study, it was assumed that all new wells are of the same pump discharge capacity of 400 gpm. An average depth for new wells in each water quality subarea is estimated in Appendix A.

Fixed costs were divided into well construction cost, pump cost, and electric motor cost. All the three component costs were calculated using empirical equations developed by Nuzman (1967). The construction (investment) cost of a well was represented by

$$I_w = 19.25\ D \quad . \ . \ . \ . \ . \quad (35)$$

where I_w is the initial investment for a well in dollars; and D is the total depth of the well in feet. The investment cost of a turbine pump was estimated by the formula

$$I_p = 519.8 + 0.3466\ Q^{0.91}\ H^{0.62} \quad . \ . \ . \ . \quad (36)$$

where Q is the discharge in gallons per minute; and H is the total head in feet. The investment cost of an electric motor was estimated from the equation

$$I_m = 341.3 + 0.0059\ Q\ H \quad . \quad (37)$$

Fixed costs were reduced to an annual cost by application of a capital recovery factor. Based on an interest rate of 12 percent and a useful service life of 20 years for the well, the pump and the motor, the capital recovery factor is 0.133879. Also, 4 percent of the investment sum was allowed for annual tax assessments and insurance costs. Therefore,

$$\begin{aligned} FC &= (CRF + 0.04)\ \{I_w + I_p + I_m\} \\ &= (0.133879 + 0.04)\ \{19.25\ D \\ &\quad + 519.8 + 0.3466\ Q^{0.91}\ H^{0.62} \\ &\quad + 341.3 + 0.0059\ Q\ H\} \\ &= 0.173879\ \{861.1 + 19.25\ D \\ &\quad + 0.3466\ Q^{0.91}\ H^{0.62} \\ &\quad + 0.0059\ Q\ H\} \quad . \ . \ . \ . \quad (38) \end{aligned}$$

where FC is the fixed costs in dollars/year/well.

Since the cost equations used above were developed based on 1963 dollars, the right hand side of Equation 38 was multiplied by a factor of 3.0 (derived from irrigation and hydro cost indexes published in the Engineering News Record) to estimate FC in 1980 dollars. Therefore,

$$\begin{aligned} FC = 0.173879 \times 3.0 \times \{ &861.1 + 19.25\ D + 0.3466\ Q^{0.91}\ H^{0.62} \\ &+ 0.0059\ Q\ H \} \quad . \ . \ . \quad (39) \end{aligned}$$

where FC is the fixed costs in dollars/year/well.

The variable cost for a new well is computed using Equation 33.

$$\begin{aligned} VC = &1.886 \times 10^{-6}\ C_k\ Q\ H\ t_h/E_f \\ &+ 0.1540\ Q^{0.47}\ H^{0.26}\ t_h^{\ 0.34} \\ &+ 0.1640\ Q^{0.84}\ H^{0.40} \quad . \ . \quad (40) \end{aligned}$$

With C_k = 4.78 ¢/kwh, t_h = 2736 hrs and E_f = 0.517, Equation 40 reduces to

$$\begin{aligned} VC = &0.0477\ Q\ H + 2.2706\ Q^{0.47} \\ &H^{0.26} + 0.1640\ Q^{0.84}\ H^{0.40} \quad . \ . \quad (41) \end{aligned}$$

where VC is in dollars/year/well.

Total annual cost per new well is now written as

$$TAC = FC + VC = 0.173879 \times 3.0 \times \{861.1 + 19.25\ D + 0.3466\ Q^{0.91}\ H^{0.62} + 0.0059\ Q\ H\} + \{0.0477\ Q\ H + 2.2706\ Q^{0.47}\ H^{0.26} + 0.1640\ Q^{0.84}\ H^{0.40}\} \quad \ldots \quad (42)$$

Since all new wells have Q = 400 gpm and by further simplifying Equation 42, we have for each water quality subarea,

$$TAC_{i\ell} = 449.18 + 10.04\ D_{i\ell} + 20.32\ H_{i\ell} + 42.1767\ H_{i\ell}^{0.62} + 37.94\ H_{i\ell}^{0.26} + 25.1521\ H_{i\ell}^{0.40} \quad . \quad (43)$$

where i represents the location, ℓ represents the water quality subarea, $D_{i\ell}$ is the depth of well in subarea $i\ell$, $H_{i\ell}$ is the depth to water level in subarea $i\ell$, and $TAC_{i\ell}$ is the total annual cost of a new well in subarea $i\ell$ in dollars/year/well.

Using values for $H_{i\ell}$ and $D_{i\ell}$ from Appendix A, $TAC_{i\ell}$ for i = 1, 2, 3 and ℓ = 1, 2, 3 were computed (Table 8). The linear programming model selects $NNW_{i\ell}$, the number of new wells in subarea $i\ell$. The total cost of the new wells equals $NNW_{i\ell} \times TAC_{i\ell}$ dollars/year. The groundwater pumped from new wells in the subarea is $NNW_{i\ell}$ times annual pumpage from one new well (201.5 ac-ft).

Canal Construction and Maintenance Costs

The waters of different qualities must be brought together for blending. This could be done by either canals or pipelines or a combination of both. For cost estimation, pipelines are used to convey water from the individual wells to a canal that in turn distributes the water to the various users.

In each location, a reasonable canal alignment (consisting of existing and new canals) was selected and used for computing costs. The canals in each location distribute waters from the center of gravity of each subarea or from the surface water source to other subareas by gravity flow. The cost of extra energy needed to overcome friction losses in piping water from wells to the canal is computed for each water quality subarea in the three locations.

An example calculation for good quality water in location 1 is presented

Table 8. Total annual cost of a new well of 400 gpm pump discharge in each water quality subarea of the three locations.

Location (i)	Water Quality Subarea (ℓ)	$TAC_{i\ell}$ (dollars/year/well)
1	Good	6159.11
1	Fair	3703.51
1	Poor	2583.82
2	Good	4209.71
2	Fair	6061.78
2	Poor	5532.57
3	Good	16151.59
3	Fair	17270.38
3	Poor	17243.05

in Table 9. Similar costs are computed for other subareas and given in Table 10. Pipeline capital costs are estimated based on a unit cost of 77¢/foot for 6.0" PVC pipe and 49¢/foot for 4.0" PVC pipe. Labor cost for laying pipes was estimated as 10 percent of the capital cost. This capital cost was annualized based on an interest rate of 12 percent and a life of 20 years.

The total cost of water conveyance through pipelines to the canal for any subarea can then be calculated by knowing the amount of water to be transported for blending and the number of wells which supply that water.

An annual cost of $2.50/ac-ft/mile of canal was estimated from Bishop et al. (1975) and consultation with SCS engineers. Since the length of canal system to bring waters of different quality together is known for each of the three locations, cost of transportation of water for blending at each location was computed and is given in Table 11. The cost of water conveyance through canals for blending for each location is obtained by multiplying the

Table 9. Estimation of conveyance cost.

Pumping capacity = 410 gpm

= 0.91 cusecs

Time to pump 1 acre-foot of water = 13.25 hrs

Average distance to the center of gravity of the area = 5280'

Assume a PVC pipe of 6.0" diameter with a friction factor of 0.018.

Velocity of flow in pipe is calculated to be 4.64 ft/sec.

$$\text{Head loss due to friction} = \frac{0.018 \times 5280 \times (4.64)^2}{2.0 \times 32.2 \times 0.5} = 64.0'$$

$$\text{Power required to overcome head loss} = \frac{62.4 \times 0.91 \times 64 \times 0.746}{550 \times 0.517}$$

$$= 9.53 \text{ kw}$$

Total energy required to transport 1 ac-ft of water = 9.53 x 13.25

= 126 kwh/ac-ft. With 4.78¢/kwh, cost of energy to

transport 1 ac-ft of water for blending = 126 x 4.78

= $6.03/ac-ft

Table 10. Costs of conveying water through pipes from individual wells to the canal.

Location	Water Quality Subarea	Conveyance Cost $/acre-foot	Pipe Dia. in Inches	Length of Pipeline (feet)	Pipe Costs Per Well Per Year (dollars)
1	Good	6.03	6.0	5280	616.00
1	Fair	4.93	6.0	7920	900.00
1	Poor	22.60	4.0	1050	740.00
2	Good	3.32	6.0	2640	295.00
2	Fair	12.24	6.0	7920	900.00
2	Poor	12.69	6.0	10560	1200.00
3	Good	2.04	6.0	1320	150.00
3	Fair	2.26	6.0	1320	150.00
3	Poor	18.12	6.0	10560	1200.00

Table 11. Cost of water conveyance through canals for blending in each location.

Location	Length of New Canal in Miles	Cost of Water Conveyance $/ac-ft/year (2.50 x Length of Canal in Miles)
1	3.3	8.25
2	4.3	10.75
3	2.3	5.75

total water obtained by blending (WUA_{i2} + WUA_{i3} + WUA_{i4}) by the corresponding unit cost from Table 11.

Land Availability Data for Tooele Valley

Data on cultivated crops and irrigated area were obtained from Tooele County assessor's office (October 1981), as shown in Table 12. Irrigated, dry farming, and arable lands available were estimated for each of the three locations from aerial photographs obtained from the Aerial Photograph Field office, ASCE - USDA, Salt Lake City, Utah. The data obtained are given in Table 13. The differences between the reported (Table 12) and measured (Table 13) areas may be due to difficulties in interpreting dry and irrigated areas on an aerial photograph. Table 14 gives the adjusted land areas used in this study for each of the three locations based on reported and measured values. Adjustment was done to allocate total reported acreage to the three study locations and was done using aerial photograph acreages and by applying judgment.

Table 12. Types of cultivated crops and irrigated area in Tooele Valley as reported October 1981.

Type of Crop	Area Cultivated (in acres)		
	Irrigated Farming	Dry Farming	Total
Winter wheat	2500	1500	4000
Spring wheat	100		100
Barley	1500		1500
Corn (Silage)	350		350
Alfalfa	5000	1000	6000
Other hay	2500		2500
Oats	100		100
Potatoes	30		30
Total	12080	2500	14580

Table 13. Irrigated, dry farming and arable lands in Tooele Valley (estimated from aerial photographs).

Location	Irrigated area (acres)	Dry farming area (acres)	Arable land (acres)
1	3760	316	8300
2	3700	3332	8350
3	1200	600	4000
Total	8660	4248	20650

Table 14. Present cultivated land and arable land available for future agricultural development.

Location	Present Irrigated Farming	Present Dry Farming	Arable land
1	3900	180	8300
2	6180	1900	8350
3	2000	420	4000
Total	12080	2500	20650

Number of Existing Major Pumping Wells

A total of 63 major pumping wells are used for irrigation and public supply as reported by Razem and Steiger (1981). These 63 wells were distributed among three water quality subareas in the three locations in the same proportions as the 32 wells for which data were available (see Appendix A for data). The estimated number of wells by quality and location are given in Table 15.

According to Razem and Steiger (1981, p. 15-26) these 63 wells supplied 17,800 ac/ft of water for irrigation, municipal, industrial, and military uses. Also, the 1977 hydrologic budget of the artesian aquifer in Tooele Valley gives an average well discharge of 28,000 ac/ft. The estimated total discharge from flowing wells of 10,000 ac/ft, therefore, indicates that almost all of the groundwater withdrawal comes from the 63 wells mentioned above and neglecting the remaining small pumped wells in the present study may cause only minute errors.

Table 15. Estimated number of existing major pumping wells in Tooele Valley.

Location	Water Quality Subarea	# of Wells
1	good	6
1	fair	10
1	poor	0
2	good	18
2	fair	8
2	poor	8
3	good	4
3	fair	4
3	poor	5
Total		63

It is assumed in this study that the farmers pump their wells 24 hours a day throughout the irrigation season for optimal efficiency. Based on the average well yield (see Appendix A) and the number of pumping wells (see Table 15) and 24 hrs/day of pumping, total groundwater pumpage is calculated to be 18,167 ac-ft/yr. This amount closely compares with the estimate of 17,800 ac-ft/yr by Razem and Steiger (1981, p. 15).

Number of Flowing Wells and Their Discharge

Thomas (1946, p. 225) reported a total of 630 flowing wells in Tooele Valley in 1941. Gates (1965, p. 37) stated that 115 flowing wells were constructed between 1941 and 1963. Razem and Steiger (1981, p. 15) assumed that approximately the same number of flowing wells existed in Tooele Valley in 1977 as in 1962, new wells having replaced ones abandoned. Thus, in this study a total of 745 flowing wells are assumed to exist. Razem and Steiger (1981, p. 15) also estimated an annual discharge of 10,000 ac-ft from flowing wells. For this study, the 745 flowing wells in the Tooele Valley were assumed to be distributed among the three water quality subareas in each of the three locations in the same proportions as the 72 flowing wells for which data were available in Razem and Steiger (1981). In computing discharge from flowing wells it was assumed that the wells are allowed to flow only during the irrigation season and that they are capped during the remainder of the year.

The data for flowing wells are in Table 16. The discharges, based on average yield and the number of wells, compared closely with those estimated by Razem and Steiger (1981, p. 15).

Data on Discharge from Springs

Razem and Steiger (1981, p. 26) report an average annual discharge of

17,000 ac-ft from springs in Tooele Valley. Thomas (1946, p. 234) estimated that about 19,500 ac-ft was discharged annually by springs in 1938-40. It was thus assumed that the annual volume of spring discharge in Tooele Valley has remained almost constant. Almost all of the discharge is from four large springs. The are Dunne's Pond Springs, Mill Pond Spring, source of Sixmile Creek, and source of Fishing Creek. Measured spring discharges for 1977 are given in Table 17. The annual spring discharges vary between 15,000 ac-ft and 21,000 ac-ft in the years 1975 through 1982. Even though the year 1977 is considered a drought year, the spring discharge for that year seems to be average.

Based on the description of how this spring water is being used in

Table 16. Number of flowing wells and their estimated discharge.

Location	Water Quality Subarea	# of Wells	Average Yield in gpm	Estimated Discharge in ac-ft
1	good	194	15.4	1493
1	fair	97	20.0	970
1	poor	38	31.0	589
2	good	45	25.4	571
2	fair	261	34.6	4509
2	poor	112	31.0	1734
3	good	0	-	0
3	fair	0	-	0
3	poor	0	-	0

Table 17. Spring discharge for the year 1977.

Spring	Location	Water Quality	Discharge in ac-ft
Dunne's Pond (C-2-4) 10 bca-S1	2	fair	6360
Mill Pond (C-2-4) 15 cac-S1	2	poor	5340
Sixmile Creek (C-2-5) 26 cdc-S2	2	poor	2780
Fishing Creek (C-2-5) 33 add-S1	1	poor	2470
Total			= 16,950 ac-ft

Steiger's report (Herbert et al. 1981, p. 9), it was assumed for the purpose of this study that approximately 3000 ac-ft of spring discharge is available annually for irrigation in the valley and that the remainder is diverted to the Jordan Valley for industrial use.

On the average, it is assumed that 800 ac-ft of poor quality water is available in location 1 (Fishing Creek), 400 ac-ft of fair quality water is available in location 2 (Dunne's Pond), and 1800 ac-ft of poor quality water is available in location 2 (Mill Pond) for uses within the valley. Since the discharge from springs is free of pumping cost, the available water from springs is handled in the LP model by adding spring water to that available from flowing wells of corresponding quality and location to reduce the number of variables.

Availability of Surface Water

Estimates of the average annual discharge of the principal streams entering Tooele Valley are given in Table 18. Two different estimates are available for some streams. The Settlement Creek Canyon has a storage reservoir, but the other streams do not. Data on surface water diversion, if there are any, were not available for this study. Therefore, the amount of surface water presently being used in the valley had to be estimated.

Records do show that 2699 ac-ft of water from the Settlement Canyon Reservoir were used for agriculture in 1980 (USDI 1981). This value was assumed to be the average annual water available from Settlement Canyon Creek. Presently, 50 percent of average annual flows from other streams is assumed to be used. For streams with two estimates, the average was used. Estimates of the total surface water available for irrigation development and the present use of surface water in each of the three locations are given in Table 19.

Population Projections for Tooele Valley

Population projections for Tooele City for the years 1980, 1990, 2000, 2010, and 2020 were taken from Hansen et al. (1979, p. 43). The 1980 populations for Grantsville City and the remaining area in Tooele Valley were obtained from Bingham Engineering (1976, p. 28).

Table 18. Estimated average annual discharge of principal streams entering Tooele Valley.

Stream	Average Annual Discharge in ac-ft: Razem and Steiger (1981, p. 6)	Average Annual Discharge in ac-ft: Bingham Engineering (1976, p. 10)
Mack and West	900	
Swenson	600	
Pine Canyon		1633
South Willow	4830	4940
North Willow and Davenport	3100	4934
Settlement Canyon	4000	6626
Box Elder Canyon	900	5377
Middle Canyon	1100	5570
Pole and Bates Canyon	1600	

These populations were then projected to years 1990, 2000, 2010, and 2020 proportional to the growth factors used for Tooele City. The above three population estimates (in locations 3, 1, and 2 respectively) are tabulated in Table 20.

Municipal and Industrial Water Requirements in Tooele Valley

The projected populations (n_t) in Table 20 are needed to estimate the returns from the public water supply systems with Equation 10. However, the total amount of water supplied to M & I uses is a decision variable in the linear programming model. The average per capita withdrawal rate for Tooele City M & I system was 0.23 ac-ft per capita per year during 1974-1976 (Hansen et al. 1979, p. 21). If the optimal amount of water selected by the LP model for supply to M & I uses is less than this amount, it would be necessary to add extra constraints to the linear programming model.

Water for Military Facilities

The average water withdrawn by the Tooele Army Depot located in Tooele Valley is 1,375 ac-ft per year and has remained almost constant in recent years. This water is obtained exclusively from groundwater (Hansen,

Table 19. Estimates of total surface water available for irrigation development (75 percent of annual average flow) and present use of surface water in Tooele Valley.

Location	Contributing Streams	Total Available Water (ac-ft)	Water Presently Used (ac-ft)
1	Mack, West, South and North Willow, Davenport, and Box Elder	9,705	6,470
2	Pole and Bates Canyon	1,200	800
3	Swenson, Pine Canyon, Middle Canyon, and Settlement Canyon	8,160	5,483

Table 20. Population projections for Tooele Valley.

Location	1980	1990	2000	2010	2020
1	4037	4724	5531	6338	7105
2	2248	2630	3080	3529	3956
3	19400	22700	26600	30400	34100
Total	25685	30054	35211	40267	45161

et al. 1979, p. 33), and the benefits are not included in the objective function of the linear programming model.

Stock Water Requirements

According to information obtained from Tooele County Assessor's Office in September 1981, there were approximately 300 cattle, 5000 sheep, and 400 horses in the Tooele Valley. Approximate water requirements for cattle, sheep, and horses are 8, 1, and 12 gallons per day per head. This amounts to about 40 ac-ft of water annually. This is a small amount compared with other beneficial uses, and poor quality water is suitable for stock watering purposes. Therefore, this use of water has been neglected in this study.

CHAPTER V

MODEL OPERATION AND DISCUSSION OF RESULTS

A number of different water supply alternatives were analyzed. The application of the static linear programming models assumed that the sources and amounts of water supply, the beneficial uses, and all constraints remain the same each year to the planning horizon in 30 years. Each static run has a particular purpose. For example, one determined whether the present pattern of use of different quality waters is optimal for the existing combination of crops. Another determined whether a more profitable combination of crop acreages could be grown from existing withdrawals. The results are discussed individually by each run and summarized in Table 21.

Run 1. To optimize use of the existing supply of water for cultivating existing crops assuming no new land is brought into cultivation.

The optimal agricultural water use pattern, in terms of quality and quantity, is much the same as the existing pattern. However, the existing water supply was short by 3260 ac-ft of meeting the M&I requirements of 5910 ac-ft. This shortage indicates one or more of the following: 1) the estimates of existing supplies are low; 2) the consumptive use estimates are high; and 3) the assumed irrigation efficiency is low. One or more of these parameters should be modified suitably when further data become available, to make the solution more realistic.

Run 2. To determine the optimum combination of crops by acreage to cultivate with the existing water supply and land.

The optimal solution indicated a much different combination of crops, met the M&I demand in full, pumped nearly 5000 ac-ft less water and improved the objective function by 50 percent. The model completely eliminated wheat, which gives full yield with poor quality water, in favor of salt sensitive crops which bring more profit.

Run 3. Same as Run 2 but with a blending option.

The blending was not profitable and optimal solutions were the same as that for Run 2.

Run 4. To determine optimum combination of crop and number of acres to cultivate with only existing water supply but new land being available for further cultivation.

All existing water supply was used for irrigated agriculture and all of the new land was brought under cultivation, most of which was used for dry farming since water supply was limited to existing supplies.

Run 5. Same as Run 4 but with the blending option.

Blending still was not profitable and optimal solutions were the same as for Run 4.

Run 6. To determine optimum combination of crop and number of acres to cultivate with no new land to be brought into agriculture but with the option for drilling new wells for additional water.

Table 21. Results of different linear programming runs.

Variables	Existing Use	Run No. 1	2	3	4	5	6	7	8	9
GWUT11	4222	4222	2405	2405	4222	4222	2405	2405	4222	4222
(NNW11)										
GWUT12	3277	3277	3277	3277	3277	3277	3277	3277	9322	9322
(NNW12)									(30)	(30)
GWUT13	1389	1022	1389	1389	1389	1389	1389	1389	9449	9449
(NNW13)									(40)	(40)
GWUT21	5576	5576	5576	5576	5576	5576	5979	5979	5979	5979
(NNW21)							(2)	(2)	(2)	(2)
GWUT22	7750	7750	7750	7750	7750	7750	7750	7750	7750	7750
(NNW22)										
GWUT23	5388	5388	5388	5388	5388	5388	5388	5388	5388	5388
(NNW23)										
GWUT31	1108	1108	0	0	0	0	0	0	0	0
(NNW31)										
GWUT32	665	665	0	0	0	0	0	0	0	0
(NNW32)										
GWUT33	1662	1662	900	900	900	900	900	900	900	900
(NNW33)										
SWUT11	6470	6470	6470	6470	6470	6470	6470	6470	9705	9705
SWUT21	800	800	800	800	800	800	1200	1200	1200	1200
SWUT31	5483	5483	5483	5483	5483	5483	8160	8160	8160	8160
M&I	5910	2649	5910	5910	5910	5910	5910	5910	5910	5910
Alfalfa	8630	8630	6339	6339	5782	5782	6931	6931	9327	9327
Corn Silage	350	350	1304	1304	1444	1444	1452	1452	2331	2331
Dry Wheat	1500	1500	2830	2830	22214	22214	1497	1497	14237	14237
Wheat	2600	2600	0	0	0	0	0	0	0	0
Barley	1500	1500	4101	4101	5781	5781	4694	4694	9328	9328
Net Benefits		1.98×10^6	3.01×10^6	3.01×10^6	3.34×10^6	3.34×10^6	3.03×10^6	3.03×10^6	3.47×10^6	3.47×10^6

Notes: $GWUT_{ik}$ = Groundwater used total in location i of quality k (ac-ft) (includes pumped wells, flowing wells and springs).

$SWUT_{ik}$ = Surface water used total in location i of quality k (ac-ft).

NNW_{ik} = Number of new wells in location i of water quality k.

Crop acreages are in acres. Net benefits are in dollars.

Not all the existing well water supply was used, and only two new wells (in the good quality subarea of location 2) were developed, extracting only 403 ac-ft of new water and irrigating 1003 acres of previously dry farm land. The objective function was increased by a slight amount, due to different crop combinations, compared with the case of no new wells (Run 2).

Run 7. Same as Run 6 but with the blending option. Blending is not used and the solutions are same as in Run 6.

Run 8. To determine optimum combination of crop and number of acres to cultivate with the option for bringing new land under cultivation and drilling new water wells for additional water (number of new wells was restricted to not more than a well per 80 acres for avoiding well interference after continuous pumping during the irrigation season nearly 4 months long).

In this solution, 8906 acres of the available 20,650 acres of new cultivable land were put under irrigated agriculture and the remaining 11,744 acres were used for dry farming. Seventy-two new wells were drilled bringing 14,508 ac-ft of additional water to use.

The results of this run are important because:

a) They show that with the current situation, with respect to crop prices and to cultivation and water supply costs, no more than 8,906 acres of the available 20,650 acres of additional land can be irrigated profitably. Therefore, it describes full agricultural development of the valley, given a maximum density of one well per 80 acres of land and the existing crops of alfalfa, corn silage, wheat and barley.

b) If full development can be assumed to occur over a short period (4 or 5 years), no further allocation models are necessary. In other words, the solution for the annual LP model of Run 8 gives the optimal allocation of water to the planning horizon on an annual basis.

c) The Aquifer Simulation Model runs indicate (as described below) that pumping an additional 15,000 ac-ft of water per year would not mine the aquifer. Even though seasonal drawdowns may increase, the behavior of the aquifer is static from period to period. This condition precludes application of dynamic programming. However, the dynamic programming scheme presented above would be a useful tool to account for user costs associated with the common property problem of groundwater withdrawals when aquifer behavior is dynamic.

Run 9. Same as Run 8 but with the blending option.

Even when all the cultivable land is made available for irrigated agriculture, blending for exploitation of the remaining available groundwater does not bring additional profits. In Runs 8 and 9, the maximum allowable number of new wells were drilled in subareas with fair and poor quality water in location 1 and in the subarea with good quality water in location 2 (30, 40, and 2 wells, respectively). In the remaining water quality subareas, the cost of a new well is nearly twice as large or more. It is almost prohibitive in the third location because of the depth to water.

When the restriction on the number of new wells (not more than one well per 80 acres) was removed, the number of new wells in the three areas changed to 27, 48, and 116 respectively. Twenty-seven and 48 are not far from 30 and 40 respectively which give a density of a well per 80 acres. However, the 116 wells in the good quality subarea of location 2 gives a density of almost a well per 1.25 acres. Since each well could irrigate more than 1.25 acres, the optimal solution indicates that much of the water should be exported. The number of wells in these locations would have been greater except the land available for cultivation and the export costs became a limiting factor.

About 5000 acres of cultivable land in the third location remain dry farmed since the optimization model transfers water within each location only and not between locations. If water could be transported from locations 1 and 2 to location 3, the number of new wells in the two lower locations may go still higher to irrigate the land in the third location. In that case, the two limiting factors will be 1) the practically allowable density of wells, and 2) the cost of transporting water under pressure to the higher elevations in location 3. If the combined cost of pumping at lower lifts in locations 1 and 2 and transporting the water to location 3 turns out to be cheaper than pumping water directly from deeper depths in location 3, this scheme will be profitable and the remaining 5000 acres in location 3 can be irrigated. This seems unlikely, but a more detailed hydrologic and economic study may be worthwhile.

The availability of surface water in Tooele Valley is limited; and to the extent that it is a less expensive source, all available surface water should be developed first. Further development of groundwater is restricted in all locations by economic infeasibility except in fair and poor quality subareas in location 1 and good quality subarea in location 2 where hydrologic factors are limiting. More new wells can be allowed in these three areas until local interference (rather than long term drawdown caused by the amount of water pumped) between wells starts to cause technological diseconomies. Further hydrologic and economic study is necessary to determine the optimal density of wells in these areas.

A few more things are to be noted regarding the proposition for pumping water in fair and poor quality subareas in location 1 and good quality subarea in location 2 and transporting it to location 3. First, a limit on the pumping rate may be necessary to maintain reasonable drawdowns and pumping costs, and the appropriate limit depends on the permeability of the aquifer material and the rate and amount of downward leakage from the water table aquifer to the artesian aquifer. Secondly, heavy localized pumping would surely cause water from other areas to migrate and would thus affect water quality. It may not be significant, however, because wheat and barley crop yields are not affected in the salinity range of Tooele Valley aquifer waters.

Aquifer Simulation

It was observed in a simulation of the Tooele Valley artesian aquifer for the period 1941-1977 (Razem and Steiger 1981) that increased pumpage resulted in a nearly equal amount of reduction in upward leakage to the water table aquifer. Most of the leakage is lost as evapotranspiration, but some is probably discharged through springs. When new wells extract more water, such as in the Run 8 solution to provide nearly 15,000 ac-ft of additional water, the upward leakage to the unconfined aquifer and the amount of evapotranspiration by phreatophytes also decrease. This interaction would continue with increasing pumpage until the water table aquifer goes dry. This situation is not handled well in the 2-D aquifer model because it does not simulate changes in water levels in the water table aquifer. The water table aquifer becomes unrealistically modeled as a a continuous source of water to the artesian aquifer.

Further groundwater development could dry most of the wet land areas in the northern valley, thus destroying many natural phreatophytes. The spring discharges may decrease or cease as actual mining of the aquifer takes place.

Behavior of the artesian aquifer was then simulated at a pumpage equal to 23,000 ac-ft (estimated present evapotranspiration or upward leakage) in excess of 15,000 ac-ft of water from new wells. The simulation reached a steady state condition at the end of 11 years due to downward leakage from the unconfined aquifer. The water table decline ranged from 5 feet at the northern edge to nearly 25 feet at the southeast corner (Figure 6).

According to the simulation, upward leakage decreased to 4000 ac-ft and downward leakage from the water table aquifer to the confined aquifer increased to nearly 24,000 ac-ft. Most of the downward leakage occurred in the central valley where irrigated agriculture is concentrated. One should remember, however, that the calculated downward leakage is based on a constant water table elevation in the unconfined aquifer. A more realistic integration of the artesian and water-table aquifer requires a three-dimensional model. Another improvement would be to model the effects of pumping on dishcarge into the Great Salt Lake.

Alternatives for Additional Groundwater Development

An attempt was made to hypothesize a few scenarios under which extraction of more water from the aquifer may be profitable.

1. Instead of using constant prices to compute agricultural revenue, demand relationships were developed using regression techniques. The resulting relationships are given in Table 22.

The optimal solution was not significantly affected by substituting price vs demand relationships for constant prices. However, solution was complicated by the additional variables and constraints. A clear-cut case for changing the relative prices would be required to justify varying the relative prices of the agricultural commodities. Therefore, constant prices were used for all inputs in this study.

2. Pumping costs were increased to reflect the additional energy required because of the simulated water table declines over 25 years (Figure 3). Run 9 was repeated with new cost coefficients.

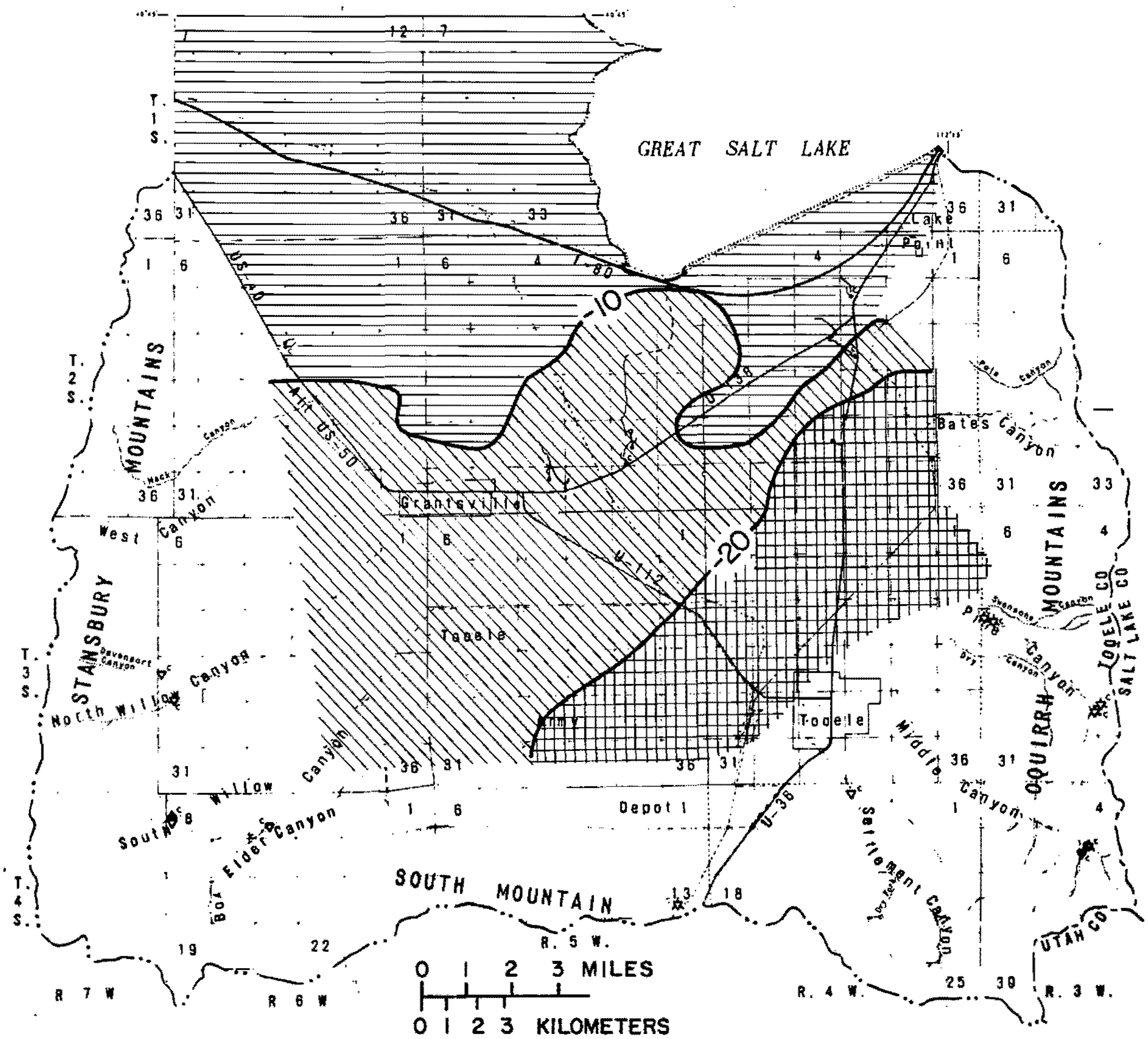
Increased pumping costs did not change the optimal solution, indicating that the problem is not dynamic in nature.

3. Prices of crops were doubled, thus increasing the benefits per unit quantity of water.

The solution indicated many more new wells for extracting nearly 40,000 ac-ft of additional water and bringing more than 18,000 acres of new land under irrigated agriculture. Blending was still not profitable. It thus seems that economic infeasibility is a major inhibitor of agricultural development in Tooele Valley rather than any hydrologic scarcity of water.

4. The slope of the linear relationship between percentage decrease in yield and electrical conductivity (a measure of total dissolved solids or salinity) of irrigation water was doubled, thus making the linear relationship steeper and the crop yields more sensitive to salts. Blending costs were reduced by 50 percent thus increasing the marginal net benefit from blending.

Making blending economically more attractive by assuming a greater crop salt sensitivity and by reducing blending costs by 50 percent was still insufficient to justify blending. This indicates that blending irrigation water is economically infeasible for agriculture involving the kinds of crops (alfalfa, corn silage, wheat, and barley) currently grown in Tooele Valley.



Base from U.S. Geological Survey topographic maps

EXPLANATION

—— -10 —— Line of equal water-level change, in feet

Decline

0 - 10 feet (0.0 - 3.0 meters)

10 - 20 feet (3.0 - 6.0 meters)

20-30 feet (6.0 - 9.0 meters)

—·· — Boundary of drainage basin

Figure 6. Predicted water-level changes in Tooele Valley for the period 1980-2010, assuming annual discharge of 69,000 acre-feet.

Table 22. Price vs quantity relationships (Q in thousand tons, t in year and P in \$/unit crop) derived from annual average price and production data for Utah for the years 1971 - 1979 (data from Department of Agriculture, State of Utah 1980).

Crop	Relationship	α_0	α_1	α_2	α_3	Standard Error of				R^2
						α_0	α_1	α_2	α_3	
Alfalfa	$Q_t = \alpha_0 + \alpha_1 t + \alpha_2 P_t + \alpha_3 Q_{t-1}$	-121517.10	62.38	-1.99	-0.04	43599.04	22.35	4.40	0.36	0.90
Corn Silage	$Q_t = \alpha_0 + \alpha_1 t + \alpha_2 P_t + \alpha_3 Q_{t-1}$	-3993.30	2.82	-37.62	0.30	50944.00	25.68	41.87	0.38	0.39
	$Q_t = \alpha_0 + \alpha_1 t + \alpha_2 P_t + \alpha_3 P_{t-1}$	30624.32	-13.97	-39.39	-56.55	50244.00	25.15	34.65	34.43	0.55
Wheat	$Q_t = \alpha_0 + \alpha_1 t + \alpha_2 P_t + \alpha_3 P_{t-1}$	-25733.71	14.57	156.10	868.73	180612.70	91.29	362.16	345.95	0.61
Barley	$Q_t = \alpha_0 + \alpha_1 t + \alpha_2 P_t + \alpha_3 P_{t-1}$	42439.00	-16.37	1780.94	-2753.55	254035.00	127.90	1791.90	1604.00	0.38

Factors which could make blending a profitable component of conjunctive water use planning include:

1) High valued crops sensitive to salt in irrigation water. Of the four major crops grown in Tooele Valley only two are salt sensitive to irrigation with the most saline groundwater available. Wheat and barley yields are not affected even when irrigated with the poor quality water of Tooele Valley. Also, crop rotation constraints require that certain amounts of these crops be grown. These crops can then use the poor quality water while reserving the good quality water for alfalfa and corn silage. Even alfalfa and corn silage are not sensitive enough to make the marginal benefits from blending exceeds its cost. Growing fruit crops like peaches, which are very sensitive to salinity and give high monetary profits, may justify a high blending cost. But, farmers may not be able to sell peaches in the market due to limited demand and other locations where their production is less costly.

2) A greater range in the qualities of natural waters. For example in Tooele Valley the approximate range of water quality is 0.4 - 3.2 mmhos cm^{-1}. If the three water qualities available were 1, 5, and 10 mmhos cm^{-1}, the yields of all four crops would have been significantly reduced and water blending would be more meaningful.

3) Less costly facilities for blending. In Tooele Valley, blending requires the construction of canals and pipelines which have high initial costs. At other locations, blending may be possible with existing facilities.

4) Greater cost savings for poorer quality water. In situations where available surface water of good quality is costly, it is more likely to be worthwhile for the farmer to mix it with the less expensive, poor quality local groundwater until the resulting water quality becomes poor enough to affect crop yields. If waters of good and poor qualities come from the same aquifer with similar pumping lifts, there is little opportunity for savings. A limited quantity of costly good quality water and relatively abundant quantity of poor quality water favor blending of waters for irrigation.

5) Greater water shortage. The relative amounts of water and land are also major factors. The crop rotation constraints in Tooele Valley are such that the amount of good quality water was nearly enough to supply the needs of the salt sensitive crops, and poor quality water could be used to grow non-sensitive crops which must be cultivated to meet crop rotation constraints.

An Extreme Example

Since many factors interact at different levels in affecting blending profitability, a situation was sought in which blending would be profitable. One hypothetical situation would be to grow peaches. The peach crop is very salt sensitive and brings high profits per unit of land cultivated. Profitable technological application of blending in irrigated agriculture of Tooele Valley was possible when it did not involve any additional costs to the farmer. Consumptive use of water for peaches is almost twice that of alfalfa and nearly 35,000 ac-ft of additional water was developed to grow 550 acres of corn silage, 4500 acres of wheat, and 10,000 acres of peaches. Almost all new land was used for dry farming and no alfalfa or barley was cultivated. This solution seems to be far from reality because 1) markets cannot absorb the amount of peaches that can be grown on 10,000 acres, 2) alfalfa is a growing enterprise in Tooele Valley and is being exported to markets outside the valley, and 3) the blending of waters of different qualities available naturally in different regions of the valley necessarily involves additional costs to the farmer. This hypothetical problem does, however, indicate that blending can be a profitable technology under certain conditions.

CHAPTER VI

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

Economical and technical feasibility studies examined the opportunity for conjunctive water use combining ground and surface waters of different qualities in Tooele Valley. The valley was divided into three locations, and each location into three subareas with good (0 - 500 mg/l), fair (500 - 1000 mg/l) and poor (1000 - 3000 mg/l) groundwater qualities. All surface water available was of good quality. A linear programming model was developed to determine whether mixing waters of different qualities and prices (due to different pumping lifts) would be less costly. The model considered field crops such as alfalfa, corn silage, wheat, and barley; and it was also extended to consider peaches in a special case. The groundwater withdrawals directed by the programming model were examined in a two dimensional simulation of the artesian aquifer to evaluate the consequences and form a tentative policy for future groundwater development in Tooele Valley. A dynamic programming scheme was developed to quantify the externalities from groundwater withdrawal due to the common property nature of the groundwater resource. However, it was not needed because pumping rates would not draw the aquifer down over the planning horizon.

Conclusions

1. The probable scenarios of future agricultural development in Tooele Valley do not require extensive groundwater withdrawals (overdrafts). Therefore, groundwater mining is not a major problem.

2. The high cost of groundwater extraction is a limiting factor for agricultural development in most parts of the valley. In fair and poor water quality subareas in location 1 and good water quality subarea in location 2, where groundwater was relatively less expensive, hydrologic factors became limiting. New wells may be located in these areas and additional groundwater may be extracted until drawdown interference among the wells starts to cause technological diseconomies.

3. Profitable application of blending technology for irrigated agriculture in Tooele Valley is not possible without making a drastic shift to high valued crops. Such a change does not now seem realistic considering the present market conditions for farm products in the valley.

4. Pumping groundwater in fair and poor water quality subareas in location 1 and good quality subarea in location 2, where it is relatively less expensive, and transporting it to Tooele City area for irrigation may be a worthwhile scheme. Should M&I demand in the Tooele City increase, the surface water available in the Settlement Canyon and the Middle Canyon may not be enough to meet both M&I and agricultural demand. This proposition, however, requires further and more detailed hydrologic and economic study using a 3-D aquifer simulation model and detailed economic data.

5. All surface water sources should be tapped before going for the more expensive groundwater.

6. An additional 20,000 to 25,000 ac-ft of groundwater extraction in Tooele Valley would not be mining the aquifer but imparts a high risk of destroying natural phreatophytes and probable degradation of water quality in the artesian aquifer. Therefore, as additional water is extracted, careful attention should be given to the proper locationing of wells and towards groundwater quality monitoring.

7. The dynamic programming scheme developed can be a useful tool to handle externality in groundwater problems subject to assumptions involved in the development of the scheme.

Recommendations for Future Study

Two modifications in the basic structure of the linear programming model may increase the effectiveness and generality of the model. They are: 1) to make crop yields a function of both water quality and quantity applied, and 2) to incorporate transfers of water among locations.

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APPENDIX A

Available data for major pumping wells used for irrigation and public supply were taken from Razem and Steiger (1981). These wells were assumed to represent average depth to water table, average pump discharge, and average depth of well of the existing pumping wells for every water quality subarea in each of the three locations.

Location 1. Subarea of good quality groundwater.

Well Number	Depth to Water Level (feet)	Pump Discharge (gpm)	Depth of Well (feet)	Use
(C-2-6) 26 dac-1	34.9	760	246	Irrigation
(C-2-6) 36 acc-2	45.0	750	465	Public supply
(C-2-6) 26 dcd-1	92.6	1200	420	Public supply
Average	57.5	903	377	

Location 1. Subarea of fair quality groundwater.

Well Number	Depth to Water Level (feet)	Pump Discharge (gpm)	Depth of Well (feet)	Use
(C-2-6) 23 cbb-1	8.2	240	210	Irrigation
(C-2-5) 33 dcd-1	18.0	360	285	Irrigation
(C-2-5) 33 dba-2	23.0	500	154	Irrigation
(C-2-6) 23 cdc-2	25.9	980	400	Irrigation
(C-2-5) 33 dad-4	35.0	210	120	Irrigation
Average	22.0	458	234	

Location 1. Subarea of poor quality groundwater.

No major wells.

Assume H = 18' and Q = 150 gpm Depth of well = 135'

Location 2. Subarea of good quality groundwater.

Well Number	Depth to Water Level (feet)	Pump Discharge (gpm)	Depth of Well (feet)	Use
(C-2-4) 33 aab-1	1.3	740	403	Irrigation
(C-2-5) 35 dbb-2	18.0	320	120	Irrigation
(C-2-4) 27 bad-1	20.5	1400	581	Public supply and irrigation
(C-2-5) 35 dbb-1	32.0	80	223	Irrigation
(C-2-4) 33 add-1	36.1	410	165	Irrigation
(C-2-4) 21 add-1	39.6	1200	90	Irrigation
(C-2-4) 28 aac-1	51.9	490	185	Irrigation
(C-2-4) 33 dac-1	55.8	120	155	Irrigation
(C-2-4) 34 bdd-2	71.1	210	254	Irrigation
Average	36.3	552	242	

Location 2. Subarea of fair quality groundwater.

Well Number	Depth to Water Level (feet)	Pump Discharge (gpm)	Depth of Well (feet)	Use
(C-2-4) 32 cbd-1	10.0	410	437	Irrigation
(C-2-4) 33 bdd-1	18.9	730	421	Irrigation
(C-2-4) 34 adc-1	98.0	480	303	Irrigation
(C-2-4) 35 cbc-1	105.0	1200	304	Irrigation
Average	58.0	705	366	

Location 2. Subarea of poor quality groundwater.

Well Number	Depth to Water Level (feet)	Pump Discharge (gpm)	Depth of Well (feet)	Use
(C-2-4) 31 dad-2	1.1	270	727	Irrigation
(C-2-4) 31 dbc-3	3.8	90	221	Irrigation
(C-2-4) 31 cda-2	5.8	480	500	Irrigation
(C-2-5) 36 dcd-1	45.5	1000	325	Irrigation
Average	14.0	460	443	

Location 3. Subarea of good quality groundwater.

Well Number	Depth to Water Level (feet)	Pump Discharge (gpm)	Depth of Well (feet)	Use
(C-3-4) 31 bba-1	356.7	470	701	Public supply
(C-3-4) 30 aac-1	382.1	630	515	Public supply
Average	369.4	550	608	

Location 3. Subarea of fair quality groundwater.

Well Number	Depth to Water Level (feet)	Pump Discharge (gpm)	Depth of Well (feet)	Use
(C-3-4) 28 cdc-1	360	N.A.	452	Public supply
(C-3-4) 32 bcc-1	497.6	330	710	Public supply
Average	428.8	330	581	

Location 3. Subarea of poor quality groundwater.

Well Number	Depth to Water Level (feet)	Pump Discharge (gpm)	Depth of Well (feet)	Use
(C-3-4) 8 aaa-1	167.0	830	675	Irrigation
(C-3-5) 36 ddd-1	366.8	490	763	Public supply
(C-3-4) 29 ccb-1	451.4	-	1000	Public supply
Average	328.4	660	813	

In 1977, 63 major wells supplied water for irrigation and public supply systems (Razem and Steiger 1981). The data above include 32 wells, approximately 51 percent of the total wells.