January 1975

Optimization of Water Allocation, Wastewater Treatment, and Reuse Considering Nonlinear Costs, Seasonal Variations, and Stochastic Supplies

A. Bruce Bishop

Rangesan Narayanan

Suravuth Pratishthananda

Stanley L. Klemetson

William J. Grenney

OPTIMIZATION OF WATER ALLOCATION, WASTEWATER TREATMENT, AND REUSE CONSIDERING NONLINEAR COSTS, SEASONAL VARIATIONS, AND STOCHASTIC SUPPLIES

by

A. Bruce Bishop
Rangesan Narayanan
Suravuth Pratishthananda
Stanley L. Klemetson
William J. Grenney

The work upon which this report is based was supported in part by funds provided by the Department of the Interior, Office of Water Research and Technology, as authorized under the Water Resources Research Act of 1964, Public Law 88-379, Project No. B-097-Utah, Agreement No. 14-31-0001-4133.

Utah Water Research Laboratory
College of Engineering
Utah State University
Logan, Utah 84322

June 1975

PRWG123-2

ABSTRACT

Two significant, interrelated water resources problems are: (1) efficiently salvaging and reusing effluent water in order to augment limited water supplies; and (2) economically managing and treating wastewater to meet water quality standards. Using systems engineering and operations research techniques, the report focuses on the optimal management and use of water of imparied quality in a water resources system, including utilization or irrigation return flows and other poor quality water, water quantity and quality management systems, and wastewater reclamation opportunities. The study develops a mathematical programming transportation or transhipment model formulated for the Lower Jordan River Basin in Utah. The model incorporated all "possible" water resources (including sequential and recycled reuse of water) to supply spatially separated multi-sector water users considering non-linear costs with economies of scale for water supply and wastewater treatment, temporal aspects of seasonality and stochastic nature of water supply and demand, and the system effects of higher wastewater treatment levels.

The results of the model runs give specific allocations of water from the available sources to meet use sector requirements over a planning horizon from 1975 to 2020. The total minimum cost of water supply and wastewater treatment allocation is reduced by considering seasonality of water requirements. Stochasticity of supply and water treatment requirements increase total allocation costs. The comparison of results from the model can be used to analyze the interdependence of water supply, water pollution control, options for water salvage and reuse in order to better plan public investment in water and wastewater management facilities.

Bishop, A. B., R. Narayanan, S. Pratishthananda, S. Klemetson, and W. J. Grenney, 1975. Optimization of water allocation, wastewater treatment, and reuse considering non-linear costs, seasonal variations, and stochastic supplies. Utah Water Research Laboratory Publication PRWG123-2, Utah State University, Logan, Utah.

KEYWORDS: Water reuse, systems analysis, linear programming, separable programming, stochastic programming, water supply, wastewater treatment, water costs, optimization.

ACKNOWLEDGMENTS

This publication is the final report of a project which was supported in part with funds provided by the Office of Water Resources Research of the United States Department of the Interior as authorized under the Water Resources Research Act of 1964, Public Law 88-379. The work was accomplished by personnel of the Utah Water Research Laboratory, Utah State University.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

CHAPTER I

WATER REUSE—SYSTEMATIC APPROACHES

Water Reuse in Water Resources Planning

Two significant, interrelated water resources problems are (1) efficiently salvaging and reusing effluent water in order to augment limited water supplies, and (2) economically managing and treating wastewater to meet water quality standards. In relation to these problems, this study is oriented toward representing the water resources system in a total context, i.e., integrated management of water supply/use and wastewater treatment systems linked by options for water reuse. Generally speaking, this departs from past research in optimization of water use which has focused on the allocation of supplies to maximize benefits from multiple water uses; on deriving operating rules for supply systems; or on the optimization of waste treatment facilities for the improvement of water quality. Through the application of systems engineer and operations research techniques, this report focuses on the optimal management and use of water of impaired quality in a water resources system. As such, the study intersects several areas of concern, including utilization of irrigation return flows and other poor quality water, water quantity and quality management systems, and wastewater reclamation opportunities.

The report presents a systems modeling approach using mathematical programming for examing the interdependence of water supply, water pollution control, and options for water salvage and reuse in order to optimally allocate water as well as public investment in water and wastewater treatment facilities.

Analyzing and evaluating alternatives for water reuse requires modeling the way in which water from various sources or origins could be used to supply the water requirements at various points for various users. The structure of the problem closely parallels the "transportation or transshipment" problem of linear programming. In previous work, simple forms of the model were developed and tested by Bishop and Hendricks (1971). Further development, application and evaluation of the transshipment model (Bishop et al., 1974) indicated its capability as a planning tool. This model considered a full range of "possible" water sources (including sequential and recycled reuse of water) to supply spatially separated multisector water users. It considered water salvage and reuse as a means of augmenting water supplies to satisfy requirements and identifies alternatives of wastewater treatment by introducing treatment options as transshipment nodes. A case study was used to illustrate how such a model might be used to develop comprehensive regional water management policies. A summary of the initial model and its solutions are reported in the following section together with the simplifying assumptions. This discussion will set the background for a theoretical discussion of the revised model, relaxing various assumptions, which follows. The balance of the report documents model input data for the case study and describes the results of the analysis.

Previous Work—Model Formulation and Results

The transportation or transshipment model (Bishop et al., 1974) was adapted as an approach to evaluate the water supply and wastewater management alternatives. This large-scale model was solved to obtain water allocation patterns at a minimum total cost for Salt Lake County, Utah, for selected planning periods over a 50 year planning horizon. An outline of the model is described as follows.

If x_{ij} is the water in acre-feet transported from the i^{th} source to the j^{th} destination or use and the cost per acre-foot to do so is c_{ij}, then the total system cost is given by:

$$TC = \sum_i \sum_j c_{ij} x_{ij} \quad \text{.....................(1)}$$

With M sources (surface water, groundwater, municipal and industrial effluents available for reuse, and import water), N destinations (municipal, industrial, and agricultural sectors and bird refuges) and L intermediate points (water and wastewater treatment plants), the following constraints have to be imposed on the system.

$$\sum_{j=1}^{N+L} x_{ij} \leqq a_i \qquad i = 1,2,...,M \quad ......(2)$$

$$\sum_{i=1}^{M+L} x_{ij} \geqq b_{ij} \qquad j = 1,2,...,N \quad ......(3)$$

$$\sum_{i=1}^{M+L} x_{i,N+v} \leqq d_v \qquad v = 1,2,...,L \quad ......(4)$$

$$\sum_{j=1}^{N+L} x_{M+v,j} - \sum_{i=1}^{M+L} x_{i,N+v} = 0 \quad v = 1,2,...,L \quad ......(5)$$

The first set of constraints states that the quantity of water shipped to all destinations and intermediate points from the i^{th} origin should be less than or equal to a_i, the quantity of water available at this source. By the second set constraints, the total quantity shipped from all origins and intermediate points satisfies the requirement b_j at the j^{th} destination. The third set represents capacity constraints on the intermediate points, d_v, denoting the capacity of the v^{th} point. The fourth type of constraints sets the quantity of inflow into an intermediate node to be equal to the outflow. The objective is to obtain x_{ij} such that the total cost is a minimum within the given constraint system. The model was solved as a general linear programming problem in the IBM/ 360 using the Mathematical Programming System (MPS/360). The model was applied in a complex setting of water supply, water reuse, and wastewater treatment systems. Salt Lake City, Utah, was selected as a case study region to provide a realistic setting for model application.

The study region, Salt Lake County, covers an area of about 780 square miles in north-central Utah which lies mainly in the lower portion (about 500 square miles) of the Jordan River Basin. The major urban center (Salt Lake City) and contiguous land areas have a wide diversity of water demands including municipal, industrial, agricultural, wildlife, and recreation. The population of the county increased from 383,000 in 1960 to 462,000 in 1968, and is expected to reach 794,000 by 1985. Water demands have increased concomitantly. Mining and manufacturing are the principal industries, but agriculture is still important in the valley. The trend is toward continued industrial development. There is no one central authority to manage water resources in the basin. Instead, there exists a large number of organizationally independent public and private agencies which have evolved over the past half century. Efforts are currently being made at the county, state, and federal levels to develop region-wide water resource and water quality management (208) plans.

The primary river in the water resources system is the Jordan River, roughly bisecting Salt Lake County into two portions. A number of smaller streams flow into the Jordan River from the Wasatch Range to the east. Groundwater is also used extensively with over 300 wells or groups of wells representing the major groundwater demands.

Water use sectors for the model are categorized as (1) irrigation, (2) industrial and commercial, (3) municipal, and (4) environmental uses. Existing levels of water withdrawals, flow requirements, and influent qualities for each sector are identified by subregions depending on the water supply systems serving the localities. There are 15 independent water conservancy districts served by four major water treatment plants. However, pipeline networks interconnect many of the districts so there is exchange of water among them. Projections of future withdrawals for the sectors and subregions were developed from relevant land use, technologic, and economic factors. Land use maps have been generated from a report developed by the Salt Lake Area Transportation Study (SLATS). The maps show industrial, commercial, agricultural, and residential land usage as surveyed in 1970 and as projected to 1995. These data, along with other pertinent information, were used to forecast trends in water usage and demands. Information on consumptive use and effluent quality was also developed from the data. This information, used to develop the quantity-quality budget, served as the basis for formulating the transportation model.

Since an important element of including water reuse as a potential source of water supply is the level of wastewater treatment and reuse technologies, treatment methods and costs to achieve a given quality level and the amount of flow to be treated were developed for various treatment processes. Water quality standards for domestic, industrial, agriculture, and recreational purposes, and on the quality level of the effluent from each user, establish the range of treatment necessary to match effluent sources with user requirements. The quality of wastewater and the quality to which it must be upgraded to meet specified uses, are analyzed in selecting unit treatment costs to be used in the transportation model. The costs include the costs of the various stages of treatment processes taking into account the capital, operating and maintenance costs for each stage with respect to the plant capacity.

The modeling effort was directed toward developing an operating model and applying it to a water resources system. All basic components of the system were incorporated into the model including water supply sources, use sectors (municipal, industrial, agriculture, etc.) effluents for reuse, and wastewater treatment operations.

The results of the optimal system configuration pertained to the resource use patterns over time. In the study area, the water treatment plants appeared to have ample excess capacity and can be expected to meet peak flows even in year 2020. Central Utah Project water, an import source for the county, was not needed until year 2000. Groundwater withdrawal seemed to be lower than the safe yield and the minimum cost solutions showed a shift to more usage of groundwater in the municipal sector and sequential reuse in the agricultural sector under high demand conditions.

Also, the solution gave insight into the wastewater management aspects. With the application of class C standards all over the basin, the existing treatment plants in four of the seven subregions in the county needed expansion according to the model results.

Besides the optimal system configuration, proposals relating to regionalization of waste treatment facilities were examined using the model. Four alternatives of wastewater handling schemes for the case study area were evaluated and the results indicated that a decentralized three-regional plant system was the minimum cost solution.

Further Analyses of Water Reuse—Model Modifications

The initial model developments and results just described were based on three types of simplifying assumptions about the system:

1. Average annual water availabilities.

2. Average annual rather than seasonal demands for water supplies.

3. Linearity of unit costs of water treatment and distribution.

In the current study the basic transportation model is modified and some simplifying assumptions are relaxed in evaluating water supply and reuse, treatment and pollution control alternatives in a region. An important question is whether or not solutions obtained are significantly different than and an improvement over the simpler model. If so, does the additional information appear to be worth the additional effort in terms of data collection, computational time, and costs?

The approach in carrying out these analyses is summarized as follows:

1. Develop and refine the systems model through disaggregation of the initial model and through expansion of the model to include seasonal variations and stochasticity in supply, and nonlinearities in cost functions.

The seasonal fluctuation in water supply and use, along with the trend in water requirements from land use change and population growth, is incorporated on a discrete time basis through manipulation of the right-hand sides of the model constraints. The analysis to be derived from the model likewise covers a wider range of questions such as the timing and location of investments on treatment facilities, distribution systems, groundwater withdrawal, and the timing and sequencing in allocation of supplies to satisfy future demands.

The introduction of stochasticity under the dynamic conditions is a further important area of inquiry. Generally, the water available from various supply sources is stochastic as are the requirement levels of various water using sectors. By assigning a proper probability distribution for these values, an optimal pattern of water allocation can be arrived at using stochastic programming techniques in conjunction with the transportation model. Chance constrained programming is applied to deal with situations where extremes are considered significant.

Recognizing that cost functions are usually nonlinear functions of the quantity of water treated or transported, techniques to account for nonlinearities are employed within the transportation model in order to yield more accurate results. Separable programming is used to deal with nonlinearities in costs while maintaining the relative simplicity of a linear programming analysis.

2. Examine various alternatives for water reuse by estimating the least cost method for satisfying projected levels of water use while meeting water quality standards.

With the expanded and disaggregated model for the study area, various alternatives for meeting water demands through wastewater reuse are analyzed. Least cost allocation patterns under various assumptions and constraints for operating the system are derived and compared. A number of important questions are analyzed in evaluating alternatives to identify least cost optimal allocation patterns for both spatial and temporal considerations. Some of these include: Is it more efficient to reuse water directly from effluent source to subsequent user or to treat wastewater at a central treatment plant and then redistribute it? How does water salvage and reuse compare with other alternative water sources such as importation or increased pumpage of groundwater reservoirs? What is the impact of water salvage and reuse on the overall costs in meeting federal and state water quality standards?

By analyzing such questions the model's capability for testing water supply and wastewater management strategies can be examined. The modeling methodology is illustrated through its application to an actual study area in order to assess its usefulness as a planning tool. This involves three areas of concern:

a. Institutional restrictions on resource allocation, in particular, pollution standards.

Water supply, as well as pollution control, operates in a mileau of institutional restrictions, often spelled out as legal requirements. Pollution standards are one such restriction. The cost of these restrictions can be evaluated by obtaining optimal solutions with and without the higher levels of treatment required by water quality standards.

b. The optimal scale as well as the timing and sequence of investment in the various facilities.

Cost functions for storage, transportation, and treatment are generally nonlinear because of scale economies and initial operation of plants below design capacities. Nonlinear relationships are incorporated into the model as linear approximations to get a more accurate solution for economic size and scale of operation of water supply and treatment facilities.

To investigate the timing of investments and the phasing-in of facilities in various locations to meet user needs, the transportation model is set in a dynamic framework simulating time by using parametric programming techniques to simulate changes in water use over time. In this way, a multi-year analysis is carried out to determine the need to build new facilities in the future.

c. The usefulness of the model for generalized application to the optimization of water supply, water reuse, and wastewater treatment systems.

The studies and analyses performed in the research are directed toward current questions of water planning and development agencies. The adequacy of the system model is assessed and conclusions drawn with regard to future water planning in a region. Present or projected demands exceed the available supply of groundwater and existing surface water sources in many parts of the country. In these water short areas water reuse should be an important consideration in extending available water supplies. The study area, the integrated urban and agricultural complex along the Wasatch Front of Utah, provides an opportune setting for systems evaluation of water reuse because it is a relatively closed system in which data can be obtained and in which exists a wide range of water management problems and alternatives.

Relation of Study to Current Literature

The use of mathematical programming models in the field of water management has been quite extensive. Various optimization techniques have found application in wastewater management, specifically, in the design of treatment plants, achieving a stipulated regional water quality goal, staging an expansion of treatment facilities, and in analyzing the problem of investment timing for the region as a whole. The application of programming models in water supply planning has been generally restricted to minimum cost allocation of municipal water. Attempts to incorporate an exhaustive set of alternatives in a multi-source, multi-sector framework, described for this study, have been made only by a few.

Linear programming applications

Linear programming (LP) is one of the most widely used optimization techniques. The popularity of LP formulation is not only in the conceptual simplicity but also the readily available software packages on computers that can efficiently handle large numbers of variables and constraints in the problem. Lynn et al. (1962) used linear programming techniques to derive the combination of treatment processes that minimize cost in removing given amounts of BOD, and also (Lynn, 1964) to solve the capacity expansion problem of waste treatment facilities subject to the availability of funds, level of treatment required, and quantity of waste.

Loucks et al. (1967) presented two LP models to determine the amount of wastewater treatment required to achieve, at minimum cost, any particular set of stream dissolved oxygen standards for a river by using the Streeter-Phelps equation for DO profile. Using the input-output framework for statewide water resources modeling, Lofting and McGauhey (1968) applied the linear programming technique to optimize allocation of water over time. Clyde et al. (1971) developed a geographical subregion LP approach to statewide water resources planning. Keith et al. (1973) used supply-demand analysis and linear programming to obtain optimal allocations in the State of Utah.

LP algorithms can also be used to solve certain classes of quadratic programming. Lynn (1966) set up a programming model to supply well water at minimum cost using a quadratic cost function.

LP technique is also used with simulation, another system analysis approach, to obtain optimal allocation. For example, Harl et al. (1971) used a river quality model in conjunction with the LP model such that the results of LP are transmitted to the Fortran river quality simulation model, which in turn alters the parameter of the LP model. The LP problem is resolved using the new parameters, and the solution is fed back to the Fortran subroutine. This process is repeated until changes in the parameters and changes in the LP solution cease.

Dynamic programming

Dynamic programming (DP) has also received wide interest in application to water resources allocation problems. The formulation of a dynamic program need not be linear, continuous, or deterministic. The technique is especially suitable for sequential decision problems. In early applications of DP, Liebman and Lynn (1966) minimized the cost of providing waste treatment to meet a specified DO standard along a stream.

Dynamic programming was employed by Evenson et al. (1969) to solve the two-dimensional multi-stage allocation problem to minimize design costs to remove a desired amount of BOD and to treat and dispose of the solids generated. An optimal investment scheme for water supply projects in response to growing demand conditions was proposed by Butcher et al. (1969) using a dynamic programming approach.

Dynamic programming was used to optimize the conjunctive use of ground and surface waters (Aron and Scott, 1971) involving several surface reservoirs, streams, recharge facilities, distribution pipelines, and aquifers. The system was decomposed into several smaller and simpler subsystems. An optimal water allocation policy for 8 years operation in 3-month intervals was obtained.

Hinomoto (1972) makes use of the dynamic programming in planning capacity expansion of water treatment systems. The concave cost function reflecting economies of scale was minimized over the solution space to yield the optimal time and size of plants' capacities. Morin (1973) applied dynamic programming to find the optimum sequencing capacity expansion of water supplies in the Ohio River Basin and the Texas River Basin.

Even though the DP technique is quite flexible and relatively simple in concept, the technique does have disadvantages. The major drawback is its inability to handle, efficiently, more than two decision varables at each stage. Other disadvantages of the technique is the requirement that the objective function and the constraints be formed by sums or products of functions of one decision variable each; solution algorithm is problem dependent, therefore, no general algorithm is available to solve dynamic programming as against linear programming. Sensitivity of the system cannot be analyzed without rerunning the problem.

Nonlinear programming

Nonlinear programming (NP) techniques have been applied to find the least-cost alternative to satisfy water demand within a region (Young and Pisano, 1970). Surface water, groundwater, desalination, and reuse of wastewater were considered as supply sources to satisfy municipal and industrial demands. Nonlinearity was introduced in processes cost and transportation cost. Examination of response surface was used as the technique to find the optimal solution. Walker and Skogerboe (1973) used the Jacobian technique to transform the constrained nonlinear problem into an unconstrained nonlinear problem in the allocation of water resources subjected quality requirements. Bajer (1974) used the differential algorithm to solve nonlinear problems of managing water quality in a river basin.

Application of nonlinear programming has been limited to systems that do not have substantial number of variables. Lack of standard algorithms and available software package is one of the drawbacks of NP techniques.

Multilevel optimization

Windsor and Chow (1972) used multilevel optimization approaches to obtain optimal design of a river basin water resource development. Nonlinear cost of each subsystem is approximated by piecewise linear function. Haimes et al. (1972) applied multilevel approaches to optimize water treatment costs of the region. The system was decomposed into 27 subsystems. The system was of linear inequality constraints and quadratic objective functions. Yu and Haimes (1974) obtained optimal policy to manage conjunctive use of groundwater and surface water using multilevel optimization approaches. Haimes and Naiuis (1974) used multilevel approaches to obtain coordination strategy for regional water resources supply and demand.

The concept of multilevel optimization is not new; however, application of this technique to water resources planning and management is relatively recent. The ability to handle any types of optimization and simulation models at lower levels is one of the most attractive features of this approach.

Integer and mixed-integer programming

Another notable optimization technique used in water resources planning and management is integer programming (IP). IP algorithms are used by Liebman and David (1968) to evaluate effectiveness of the three approaches suggested in the literature to achieve water quality goals, viz. the cost minimization approach, uniform treatment approach, and zoned uniform treatment approach. Regev and Schwartz (1973) take up the problem of simultaneous optimization of investment and allocation of water. A discrete time control theory is applied in which interaction of regional and seasonal considerations plays a crucial role. The cost functions reflecting increasing returns to scale were treated as integer variables, so that theoretically a global optimum will be guaranteed.

Cost of development of various components in a water resources system exhibit "economy of scale" characteristics, i.e., as the components increase in size, costs per unit size decrease. The cost function can then be better approximated by a nonlinear function (Koenig, 1967; Linaweaver and Clark, 1964).

There are, strictly speaking, two approaches of handling nonlinearity in the cost function. The first is by using NP technique. The second is by the approximation of the cost function by a number of linear segments then applying a variation of LP algorithm to solve for the optimal solution.

Mixed integer programming is a combination of integer and linear programming. The technique allows discrete variables to be included in linear programming considerations. Hughes and Clyde (1973) applied the formulation in designing a municipal water supply system utilizing surface and groundwater sources as well as physical aspects of the system. Constraints considered were supply, blending, reservoir, developed facilities, and stochastic constraints. DeVries and Clyde (1971) considered a municipal water supply system utilizing singly or in combination a conventional water supply, a desalted water supply and a supply from a recharged aquifer. The system is also operated in conjunction with an artificially recharged aquifer reservoir. Logarithmic transformation is used to change the nonlinear cost function into ordinary LP formulation. Mulvihill and Dracup (1974) used the concept of inner linearization to approximate the nonlinear cost function. The optimal allocation, sizing, and timing is obtained through iterative procedure.

A standard software package is now available from many computer manufacturers that is capable of solving standard variations of LP formulation such as separable programming and stochastic programming (Burroughs, 1973).

CHAPTER II

MODEL REVISION FOR ANALYSIS OF WATER REUSE IN WATER RESOURCES SYSTEMS

Modifications in the Basic Transportation Model of Water Reuse

The previous chapter outlined the work of an earlier study in which certain simplifying assumptions were made. This chapter describes several model revision, relaxing these simplifying assumptions, and presents their theoretical basis.

Nonlinear cost formulation

The assumption of constant linear costs is unrealistic in that it does not reflect the "fixed charge" nature of the capital stock in the system facilities or the decreasing nature of the total average cost of the system facilities due to economics of scale.

In general, if the cost c_{ij}, of supplying the water from the i^{th} source to the j^{th} user depends on the quantity supplied x_{ij}, then the total cost can be given by

$$TC = \sum_i \sum_j c_{ij} \; (x_{ij}) \; \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Now, the problem is one of minimizing expression (6) subject to constraint sets (2), (3), (4), and (5) indicated in Chapter I. In contrast to the objective function in expression (1), the total cost in (6) is now nonlinear and is estimated as a log-linear relationship of the form,

$$c_{ij} \; (x_{ij}) = A_{ij} \, x_{ij}^{\alpha_{ij}} \quad \forall \, i, j$$

in which

$$0 < \alpha_{ij} < 1 \quad \text{and} \quad A_{ij} > 0$$

Therefore, the total cost can be given by

$$TC = \sum_i \sum_j c_{ij} \, (x_{ij}) = \sum_i \sum_j A_{ij} \, x_{ij}^{\alpha_{ij}} \quad \ldots\ldots (7)$$

Minimization of (7) subject to the linear constraints (2), (3), (4), and (5) requires a nonlinear programming method.

Before going into the selection of the algorithm to solve such a problem, the qualitative analysis of this problem should be understood. Since the constraint equations are all linear, the set of feasible solutions (if they exist) is a closed convex set bounded from below (due to the non-negativity restrictions). The total cost for any i and j is given by

$$c_{ij} \, (x_{ij}) = A_{ij} \, x_{ij}^{\alpha_{ij}} \quad 0 < \alpha_{ij} < 1 \quad A_{ij} > 0 \quad \ldots\ldots\ldots (8)$$

This function is strictly concave in the range $0 < x_{ij} < a$ due to the fact,[1]

$$A_{ij} \, \lambda^{\alpha_{ij}} x_{ij}^{\alpha_{ij}} > A_{ij} \, \lambda \, x_{ij}^{\alpha_{ij}} \text{ for any } \lambda, 0 < \lambda < 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

The sum of the strictly concave functions is also strictly concave and, therefore, the objective function (7) is strictly concave. The model in a two-variable case can be shown in Figure 1.

ABCDEF represents the convex set of feasible region and the curves TC_0, TC_1, and TC_2 represent the strictly concave objective function for various total costs. The global minimum is shown to be at point E for a total cost of TC^0 with the optimal solution being (x_{11}* and x_{12}*). In general, if the feasible region is convex and the objective function is concave, it can be proven that the global minimum will be taken on at one or more extreme

[1]A function $f(x_{ij})$ is concave between any two points 0 and any point x_{ij} if for all λ, $0 \leq \lambda \leq 1$, $f[\lambda \, x_{ij}] \geq \lambda \, f(x_{ij})$.

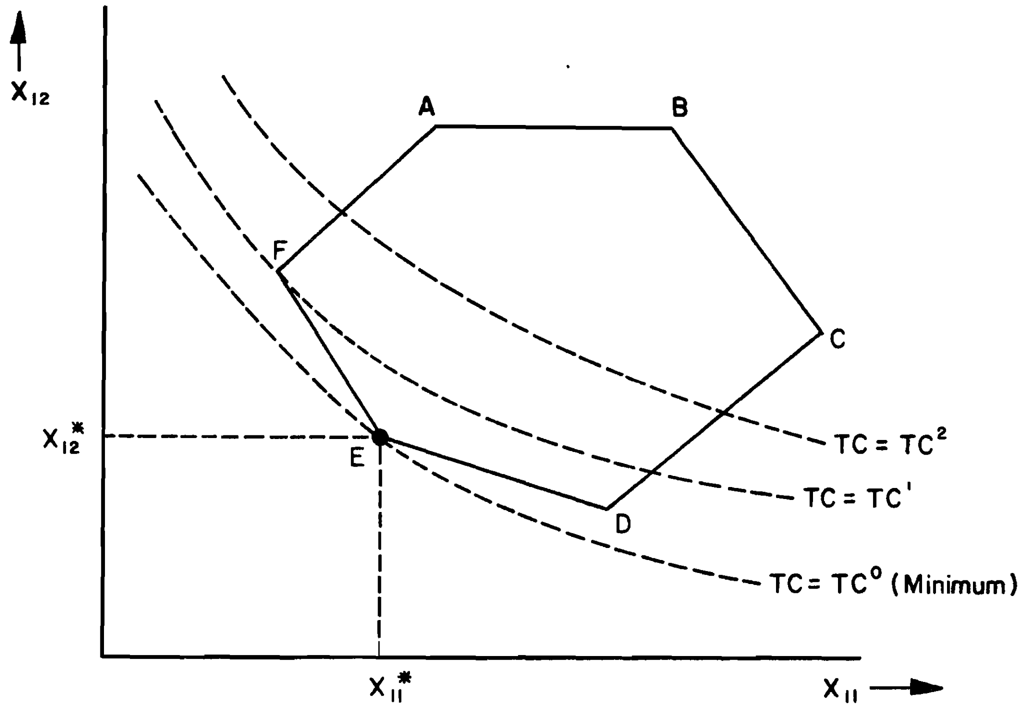


Figure 1. Model illustration for linear constraints and concave objective function for two-variable case.

points of the convex set, indicating the possibility of the existence of multiple optima (Figure 2). Although the fact remains that the global minimum occurs at an extreme point, it is difficult to make use of this property in practice to determine the global extremum. If there happens to be a relative minimum at an extreme point different from the global, such that the function value at adjacent extreme points to this relative minimum is greater, then the procedure like simplex method will terminate. Such a situation is shown in Figure 3.

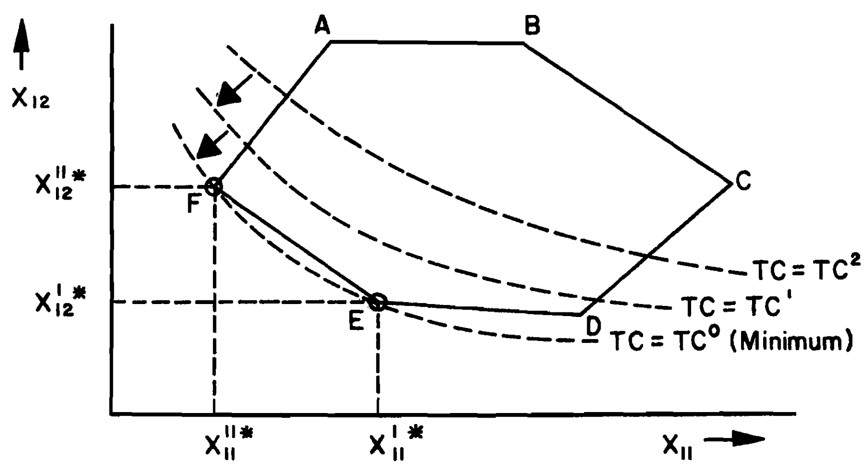


Figure 2. Illustration of global minimum and multiple optima for linear constraint concave objective function example.

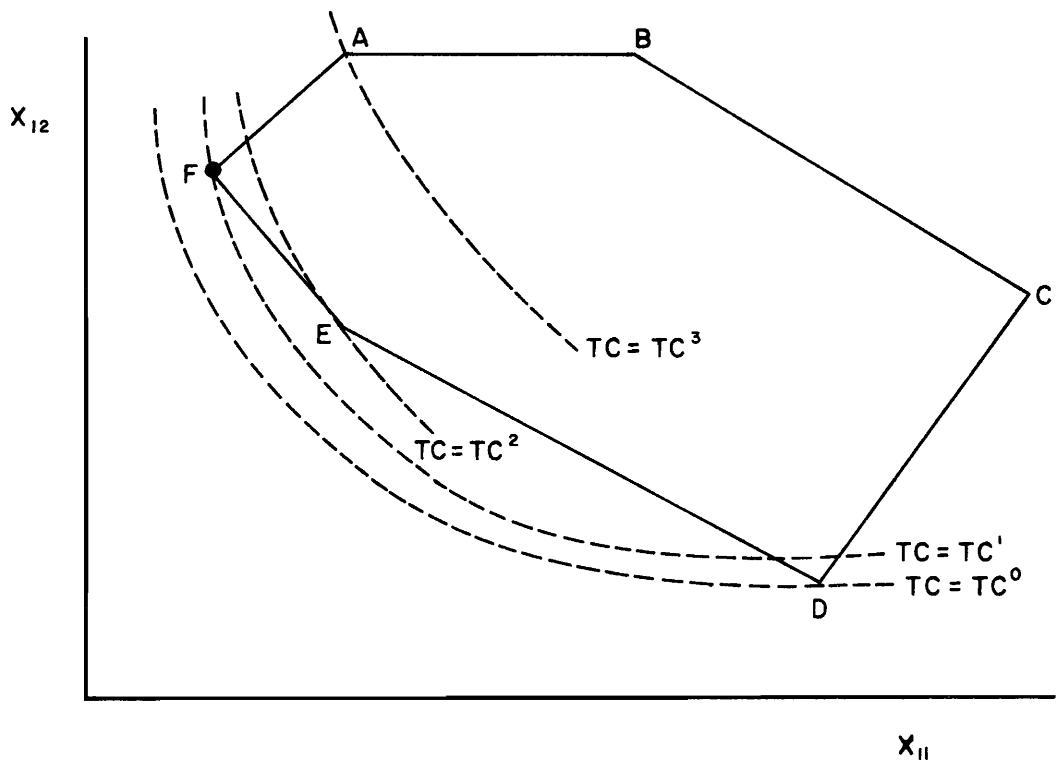


Figure 3. Illustration of the problem of a relative optimum solution for the linear constraint—concave objective function problem.

ABCDEF is the convex set of feasible region. Suppose the initial basic feasible solution is found at A. The greatest decrease in the value of the total cost will be obtained by a movement to point F where the cost is TC^1. Further decrease in cost is not possible by moving to the adjacent points A or E. Therefore, the simplex methods which moves the solution from one extreme point to the other (where the greatest possible decrease in the objective functiion is attainable) will terminate at this relative optimum. The absolute minimum is taken on at D for a total cost of TC^0.

Although many nonlinear programming methods are available to minimize (7) subject to (2), (3), (4), and (5) the question of which method to employ has to be settled mostly by past experience. Two difficulties arise, (1) generally, nonlinear programming algorithms are capable of handling only small-scale problems and thereby tend to be more specialized in their application. Most of these methods do not make use of the particular properties of this problem, viz., the convex set of feasible region is formed by a set of linear constraints and since the objective function is concave, the optimal solution will be taken on at one or more extreme points. (2) There is a tradeoff between the size of the model (and the amount of information derivable from the results) and the resources expended in solving the problem. Considering all these factors, the separable programming method was chosen.

Separable Programming Model

The concave nonlinear objective function is separable since the total cost can be expressed as

$$TC(x) = \sum_i \sum_j c_{ij} (x_{ij}) \quad \ldots\ldots\ldots\ldots\ldots (10)$$

Therefore, a piecewise linear approximation to the above function can be found as follows. Consider a single continuous function $c_{ij}(x_{ij})$ in Figure 4. The nonlinear function $c_{ij}(x_{ij})$ is shown in thick line and the polygonal approximating function is shown in the dotted line. Any x_{ij} between the arbitrary interval x_{ij}^k and x_{ij}^{k+1} can be expressed as

$$\lambda\, x_{ij}^{k+1} + (1 - \lambda)\, x_{ij}^k \text{ for all } \lambda,\ 0 \geq \lambda \geq 1 \ldots (11)$$

Therefore the true function value

$$c_{ij}\left[\lambda\, x_{ij}^{k+1} + (1 - \lambda)\, x_{ij}^k\right] \ldots\ldots\ldots\ldots\ldots (12)$$

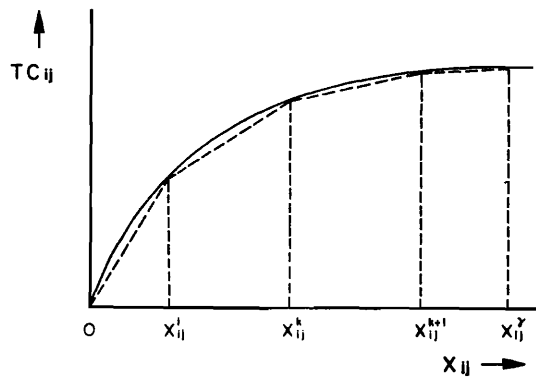


Figure 4. Piecewise linearization of a nonlinear cost funtion.

can be approximated by the function value on the linear segment given by

$$\lambda c_{ij}(x_{ij}^{k+1}) + (1 - \lambda) c_{ij}(x_{ij}^{k}) \text{ for all } \lambda, 0 \geq \lambda \geq 1.$$

In fact, between the range 0 and x_{ij}^{r}, the maximum possible value that the variable x_{ij} could assume, can be broken down into r subintervals (not necessarily uniform) and any x_{ij} in this range can be expressed as

$$x_{ij} = \sum_{k=0}^{r} \lambda_{ij}^{k} x_{ij}^{k} \quad \ldots\ldots\ldots\ldots\ldots\ldots(13)$$

in which $\lambda_{ij}^{k} + \lambda_{ij}^{k+1} = 1$ for any k between 0 and r. It follows that no more than two λ_{ij} could be positive and they should be adjacent. Similarly, $c_{ij}(x_{ij})$ in the range $0 \leqslant x_{ij} \leqslant x_{ij}^{r}$ can be approximated by

$$c_{ij}(x_{ij}) = \sum_{k=0}^{r} \lambda_{ij}^{k} c_{ij}(x_{ij}^{k}) \ldots\ldots\ldots\ldots(14)$$

in which again $\lambda_{ij}^{k} + \lambda_{ij}^{k+1} = 1$ for any k, $0 \leqslant k \leqslant r$. Since no more than two λ_{ij} could be positive and those λ_{ij}'s which assume positive values should be adjacent, in general, the function can be expressed as

$$c_{ij}(x_{ij}) = \sum_{k=0} \lambda_{ij}^{k} c_{ij}(x_{ij}^{k})$$

$$\sum_{k=0}^{r} \lambda_{ij}^{k} = 1$$

$$\lambda_k \geq 0 \quad k = 0, 1 \ldots r \ldots\ldots\ldots\ldots(15)$$

and no more than two λ_{ij} are allowed to be positive and they should be adjacent. The new total cost function to be minimized becomes

$$TC(x) = \sum_{i} \sum_{j} \sum_{k} \lambda_{ij}^{k} c_{ij}(x_{ij}^{k}) \ldots\ldots\ldots(16)$$

and the constraint set becomes

$$\sum_{k=0}^{r} \sum_{j=1}^{N+L} \lambda_{ij}^{k} x_{ij}^{k} \leqq a_i \qquad i = 1,2,\ldots,M \ldots.(17)$$

$$\sum_{k=0}^{r} \sum_{i=1}^{M+L} \lambda_{ij}^{k} x_{ij}^{k} \geqq b_j \qquad j = 1,2,\ldots,N \ldots.(18)$$

$$\sum_{k=0}^{r} \sum_{i=1}^{M+L} \lambda_{i,N+v}^{k} x_{i,N+v}^{k} \leqq d_v \quad v = 1,2,\ldots,L \ldots.(19)$$

$$\sum_{k=0}^{r} \sum_{j=1}^{N+L} x'_{i,N+v} = 0 \qquad v = 1,2,\ldots,L \ldots.(20)$$

$$\sum_{k=0}^{r} \lambda_{ij}^{k} = 1 \qquad i = 1,2,\ldots,M; j = 1,2,\ldots,N \ldots(21)$$

$$\lambda_{ij}^{k} \geq 0, k = 0, 1, \ldots, r; \text{ for } \forall\, i, j \ldots\ldots\ldots(22)$$

and that no more than two λ_{ij} can be positive for any given i and j and they must be adjacent.

With all the above constraints imposed on the system, the simplex method can now be used to obtain the optimal solution. The only special constraint required is that the basis entry should be restricted. Since λ_{ij}^{k} is the new variable replacing the x_{ij}, the basis can contain, for any given i, j, at the maximum two λ_{ij}, say, λ_{ij}^{k} and λ_{ij}^{s} such that s = k + 1 or k - 1.

Using this formulation known as the "Lambda" method, the transshipment model can be set up for the case study area. The specific model development is explained in greater detail in a later section. The solution was obtained using the Mathematical Programming System called TEMPO available with the Burroughs 6700 computer.

Seasonal variations in the model parameters

In the initial model, the solutions were obtained for the case study area with annual flows. It was assumed that the flow rate was constant at all points in time throughout the year. In reality, extensive variations in the flow rates of surface water and in the quantity of water required for various purposes vary with seasons, time of year, even to the time of day. Particularly for this analysis, seasonal changes affect the system results considerably and, therefore, the water budgeting procedure was carried out for each season and the water availabilities and quantities required were estimated. With these values, the transshipment model was solved to appraise the system operation over seasons of a year and over future years.

Stochastic Considerations

In a general programming model of the form,

$$\text{Min} \quad Z = f(\bar{x}) \qquad \ldots\ldots\ldots\ldots (23)$$

$$\text{Subject to} \quad \bar{g}(\bar{x}) \gtreqless \bar{b}$$

$$\bar{x} \geq 0 \qquad \ldots\ldots\ldots\ldots (24)$$

(1) The parameters of the objective function $f(\bar{x})$, (2) the parameters of the constraint equations $\bar{g}(\bar{x})$ and (3) the right-hand-side elements of $\bar{b}$ can be random. For the transportation model under consideration, all the coefficients of $\bar{g}(\bar{x})$ are 0, 1, or -1, and they are fixed. Therefore, randomness can be found only in the cost function parameters $f(\bar{x})$ and the elements of $\bar{b}$. It will be assumed that the cost coefficients are deterministic and only the randomness in the elements of $\bar{b}$ will be treated.

Suppose the k^{th} constraint

$$g_k(\bar{x}) \leq b_k \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (25)$$

is desired to hold with at least a probability of 95 percent, when b_k is assumed to be a normal random variate. This can be written as

$$\Pr\left[\, g_k(\bar{x}) \leq b_k \,\right] \geq \beta_k \qquad \ldots\ldots\ldots\ldots (26)$$

in which $\beta_k = 0.95$

Subtracting $E(b_k)$ where E denotes expectation operator, from both sides of the inequality within the square brackets and dividing by σ_{b_k}, the standard deviation of b_k, we have

$$\Pr\left[\frac{g_k(\bar{x}) - E(b_k)}{\sigma_{b_k}} \leq \frac{b_k - E(b_k)}{\sigma_{b_k}}\right] \geq \beta_k \qquad \ldots (27)$$

The quantity $Z = \dfrac{b_k - E(b_k)}{\sigma_{b_k}}$ is a standard normal variate $\sim N(0,1)$. If the probability density function of Z is $\Psi(Z)$, then

$$\psi^{-1}(\beta_k) = k_{\beta_k} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (28)$$

which can be obtained from a table of distribution of standard, normal, random variables. Equation (27) can be true if and only if

$$\frac{g_k(x) - E(b_k)}{\sigma_{b_k}} \leq k_{\beta_k}$$

or

$$g_k(\bar{x}) - E(b_k) \leq k_{\beta_k}\sigma_{b_k}$$

$$g_k(\bar{x}) \leq E(b_k) + k_{\beta_k}\sigma_{b_k} \qquad \ldots\ldots\ldots\ldots (29)$$

Equation 29 is a deterministic linear constraint if $g_k(x)$ is linear and assures that the k^{th} constraint will hold with 95 percent probability. This approach is known as the chance-constrained programming and was originally developed by Charnes and Cooper (1963). Using this method, the stochasticity in the random right-hand-side elements will be accounted for.

Summary of Model Runs for the Case Study Area

The various structural changes in the basic transportation model described above were used in a number of different combinations as shown in Table 1. For each of these combinations, optimal solutions were obtained for the target years of 1975, 1980, 1985, 2000, and 2020 in order to determine the effects of each set of modifications. The results of this analysis are presented in Chapter IV.

Table 1. Summary of model runs under various model structures.

Run Combinations	Cost Function		Spatial Resolution		Time Period		Treatment Level		Demand/Supply Characteristics	
	Linear	Nonlinear	7-Subregion	3-Subregion	Annual	Seasonal	Secondary	Higher Levels as Per PL 92-500	Deterministic	Stochastic
Phase I 1	x		x		x		x		x	
2		x	x		x		x		x	
3		x		x	x		x		x	
4		x		x	x			x	x	
5		x		x		x	x		x	
6		x		x		x		x	x	
7		x		x	x		x			x
8		x		x	x			x		x

CHAPTER III

WATER RESOURCES AVAILABILITY, WATER REQUIREMENTS, AND WATER REUSE COSTS

Water supply in the study area can be drawn from various available sources. Surface water is drawn from the Jordan River and the Wasatch Front streams and their associated storages; imported water through various canals and aqueducts; and groundwater through a system of wells and springs. Municipal and industrial effluents are included as alternative water supply sources through water reuse.

In addition to annual study, the water availability and water requirements were arbitrarilly divided into two seasons, namely, the winter season, lasting between the month of October till the month of March, and the summer season, commencing in April and ending in September. The summer season approximately corresponds to the irrigation period in the area.

Surface Streams Water

There exists two major sources of surface stream water sources: The Jordan River and the Wasatch Front streams. The Oquirrh Mountains streams are generally ephemeral streams with insufficient flow to be developed economically into reliable supply sources. Table 2 shows the long-term annual and seasonal means of the Jordan River at the stations near the Narrows, and the Wasatch Front streams—the Big Cottonwood Creek, the Little Cottonwood Creek, Mill Creek, Parley Creek, Emigration Creek, City Creek, and Red Butte Creek. The 95 percent supply availability by normal deviation assumption and by rank for seasonal flow is also included in Table 2. Zero flow was substituted where the computation of flow was negative, since negative flow is physically impossible.

Jordan River

The Jordan River is the single largest surface water source in the study area. The long-term average annual flow, over a 58 year period, of the river entering the Salt Lake County at the Narrows is almost 260,000 acre-feet which is more than the total combined flow of the Wasatch Front streams. The Jordan River water has been largely diverted for irrigation purposes while a small amount has been diverted for industrial consumption.

The Wasatch Front streams

The Wasatch Front streams which are the major tributaries of the Jordan River in the study area, are the Big Cottonwood Creek, Little Cottonwood Creek in subarea F2, Mill Creek in subarea G, Parley Creek, City Creek, Emigration Creek, and Red Butte Creek in subarea E. The total combined flow available from these creeks is approximately 142,000 acre-feet annually. Most streams were well developed as sources of supply in the study area, including the construction of a number of reservoirs and diversion canals.

Groundwater

Groundwater in the study area is obtained through well pumping and free flowing springs. The amount of groundwater utilization in the area has been increasing. In the past decade, the average groundwater utilization was well over 100,000 acre-feet per year (Figure 5). Since the safe yield of groundwater in the area is approximately 150,000 acre-feet per year (Table 3), the groundwater use is reaching its maximum potential without possible groundwater mining. Groundwater is used for various purposes but mainly in agricultural sectors.

Imported Water

The study area imports a relatively small amount of water from nearby sources. The existing imports are through the Salt Lake aqueduct for municipal supply, the Provo Reservoir Canal, the Utah Lake Distributing Co. Canal mainly for irrigation, and Kennocott Copper Pipeline mainly for industrial uses. In the future, an additional imported source will be available through the

Table 2. Surface water availability in Salt Lake County.

Stream Name	Length of Record (Year)	Average Flow Volume[a]			95% Flow Volume			
					Normal Dev.		Rank	
		Oct-Mar	Apr-Sep	Annual	Oct-Mar	Apr-Sep	Oct-Mar	Apr-Sep
Jordan River @ Narrow	1914-1972	55,200	204,500	259,700	0[b]	120,200	5,600	137,600
Little Cottonwood Ck.	1923-1968	5,700	37,500	43,200	3,600	23,500	4,400	21,600
Big Cottonwood Ck.	1905-1968	10,400	42,400	52,800	5,400	21,600	6,600	20,500
Mill Ck.	1900-1968	3,200	7,500	10,800	1,600	2,900	1,900	3,700
Parley Ck.	1911-1968	3,900	13,200	17,100	1,700	1,300	2,000	2,800
Emigration Ck.	1911-1968	800	3,300	4,200	100	0[b]	200	600
Red Butte Ck.	1943-1972	700	1,700	2,500	300	300	300	300
City Ck.	1912-1968	2,900	8,500	11,400	2,100	3,600	2,000	3,700

[a]Volume in ac-ft.

[b]Zero is substituted in lieu of negative flow.

Table 3. Estimated safe yield of groundwater in each subarea of the study.

Area	H1	H2	G	F1	F2	E	D
Safe Yield (ac-ft/year)	17,800	3,500	28,000	6,500	20,000	28,000	46,200

Central Utah Project which will import water from the Colorado River Basin. The Central Utah Project will supply water for various purposes west of the Jordan River.

Effluent Sources

There exists large amounts of effluent discharge in the Lower Jordan River Basin. The effluent is directly or indirectly discharged into the Jordan River or conveyed to be discharged into the Great Salt Lake. The municipal effluent discharge was about 80,000 acre-feet in 1971, while the industrial effluent total was around 100,000 acre-feet. Therefore, if the effluent water is reclaimed, it could represent a significant source of supply. With consideration of future standards to be imposed on the effluent before discharge into receiving water, reuse of effluent as alternative source is becoming more attractive.

Water Quality

The quality of water in the study area and standard requirements for various uses are well summarized elsewhere (Bishop et al., 1974). In this study, the effect of raising effluent discharge standard in 1980 and 1985 and thereafter to secondary and tertiary levels respectively is included in the system allocation.

Water Requirements

Water requirements in the study area are municipal, industrial, and agricultural and, in addition, the requirements for management of waterfowl area at the mouth of the Jordan River.

Municipal requirements

Municipal uses in the area are domestic uses, commercial and small industrial uses. Domestic uses included household uses and lawn and garden watering. During summer season, water used for lawn sprinkling and gardening accounted for about half of the total municipal use. Approximately 70 percent of the lawn water is consumed with estimated 30 percent percolated to groundwater system. During winter season watering lawn and garden is assumed to be nil. All the water used is assigned to other uses, with approximately 45 percent assumed to return to the sewer system.

Figure 6 shows the pattern of municipal uses over 21 years between October 1952 and September 1973. Data was obtained from the Salt Lake Water Department which supplies most of water services in Sale Lake area. The municipal uses average about 142 gallons per capita per day (gcd) and 300 gcd for winter and summer season respectively, with an annual consumption of 221 gcd average

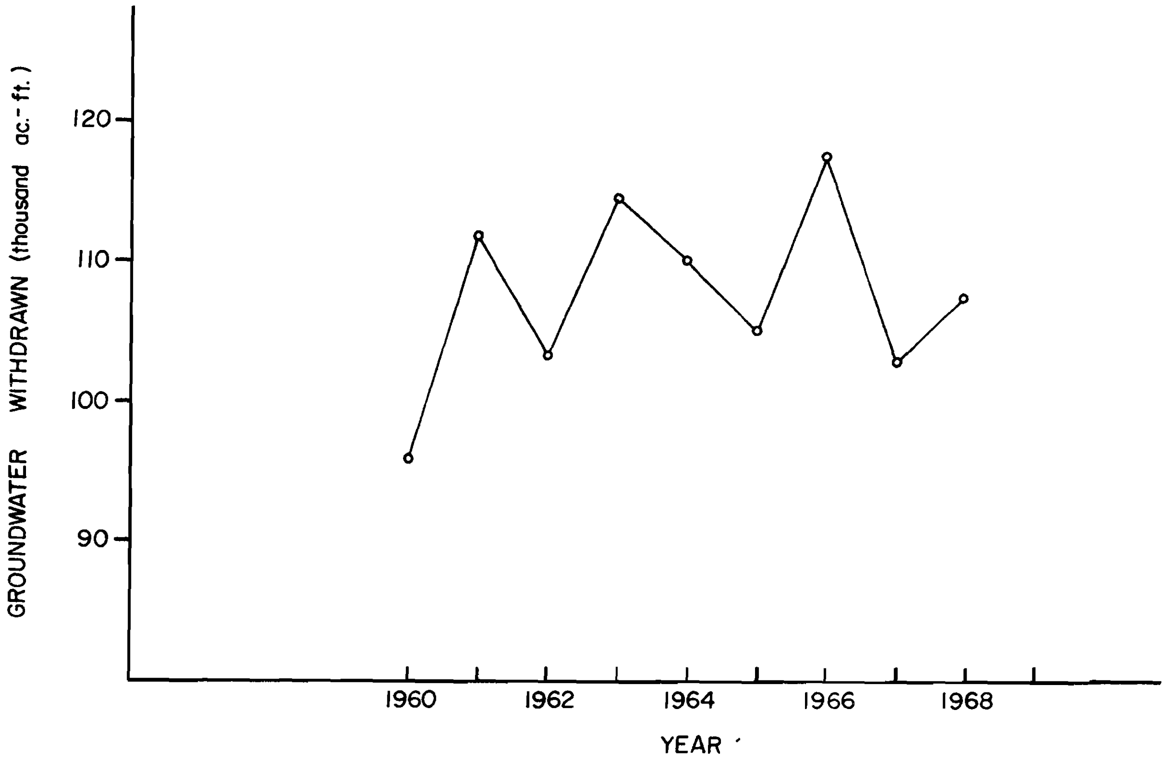


Figure 5. Groundwater withdraw for all purposes in Salt Lake County (1960-1968).

(compared with 224 gcd used in a previous report (Bishop et al., 1974)). Analysis of data did not indicate any significant trend in water uses, therefore it is assumed that uses are constant throughout the study. Table 4 shows the mean and 95 percent normal deviation water requirements in the study area for the winter and summer seasons and the annual.

Table 4. Municipal water uses in Salt Lake City serviced by Salt Lake City Water Department during the period October 1952—September 1973.

Periods	Mean (gcd)	95% Normal Deviate
Winter	142	115
Summer	300	248
Annual	221	

Variation of uses during summertime could well be explained in terms of precipitation availability. The major municipal use during summer is lawn and garden watering, and in wet summers water use was relatively low while in dry summers water use was relatively high.

Industrial uses

The industrial uses in the area are assumed to be approximately constant throughout the year. The industrial uses are also assumed to be relatively constant throughout the period of study with the exception of subarea E, containing Salt Lake City, in which small amounts of increases industrial uses are expected.

Agricultural uses

The main agricultural use is irrigation. Domestic stock is the second major use. Irrigation in the study area occurs largely between April and October. The amount of irrigation water used in October is relatively small; therefore, it is assumed that all the requirement for irrigation occurs between April and October. It is further assumed that irrigation use reflects total use in the agriculture sector. Losses due to seepage in canals

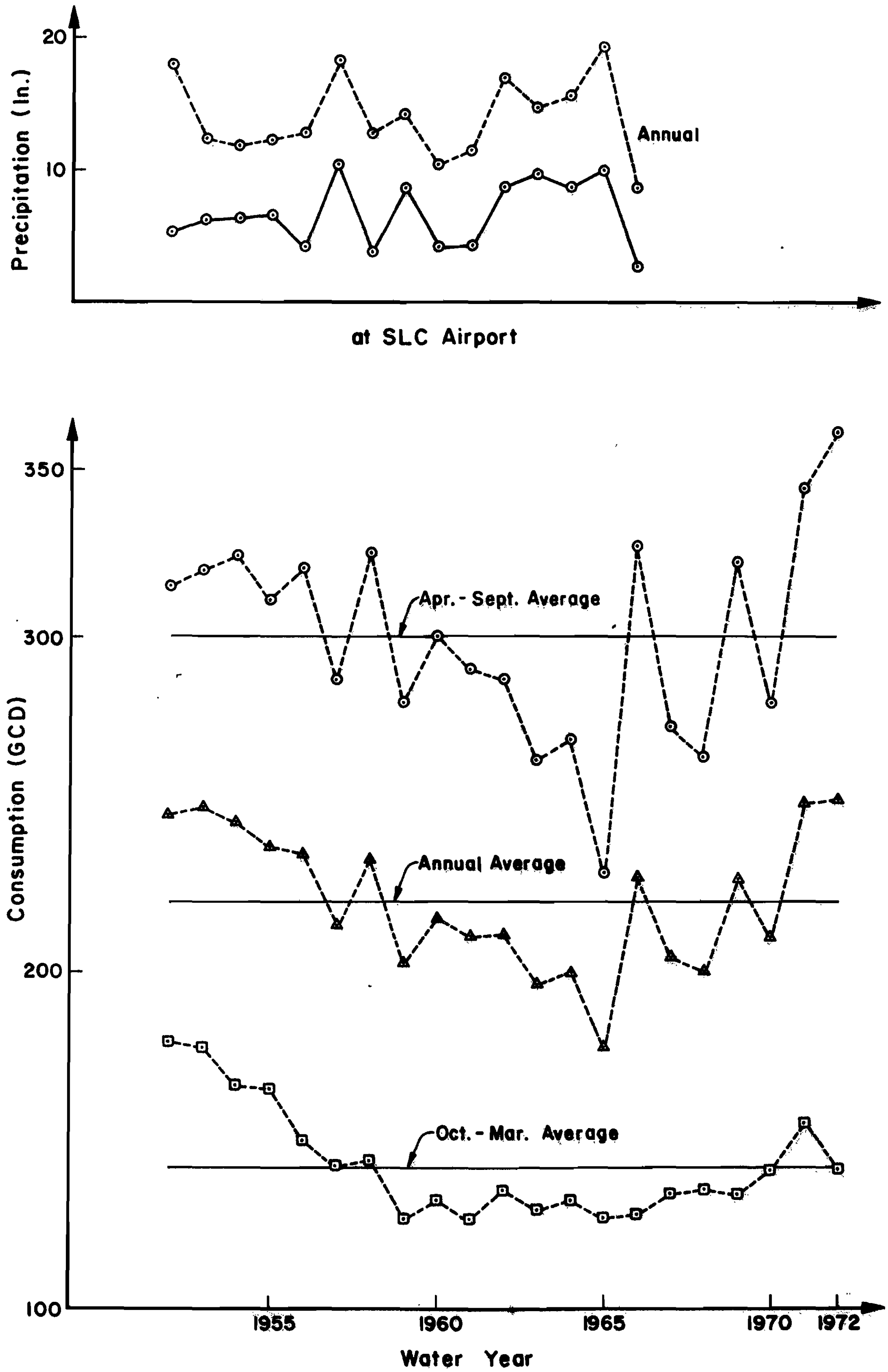


Figure 6. Comparison of municipal water consumption and precipitation.

and delivery systems are assumed to be 15 percent of diversion. Of the total field delivery, about 10 percent is assumed to return to surface water sources, about 30 percent goes to groundwater, and the rest is consumed (Hely et al., 1970).

To compute the 95 percent level of agricultural use, certain assumptions about crops and climatic conditions have to be made. In light of reducing acreage of crop land, it is expected that in the future cash crops will be more attractive. However, it is safe to assume that certain crops which require larger amounts of irrigated water are goint to be planted. Alfalfa and sugar beets are assumed to be the selected crops. Both crops require approximately the same amount of irrigation water over the season. The 95 percent requirement is then computed from monthly moisture requirement of the crop given that the natural available precipitation and temperature are 95 percent of average. Irrigation practices are assumed to have varied efficiency. The diversion requirement for each level of irrigation efficiency is shown in Table 5.

Table 5. Irrigation diversion requirement at 95 percent level.

Consumptive	Efficiency		
in/acre	30	50	70
35.03	116.8	70.1	50.0

Water Reuse Costs

The cost matrix forms the basis for decision-making in the linear programming transportation model. The literature was reviewed to determine the appropriate cost functions for each method of waste treatment and water reuse, and for water and wastewater transportation. The construction costs were then ajusted to June 1974 by the use of the ENR Building Cost Index. The operation and maintenance (O&M) costs are adjusted by the use of the labor rates for sanitation workers, published by the Bureau of Labor Statistics. The water transportation costs were adjusted by the use of the EPA sewer construction cost index (Figure 7 and Table 6). The annual cost of the capital investment was based on 5½ percent for 30 years with a capital recovery factor (CRF) of 0.069.

A summary of the cost equations for the total cost of water treatment and reuse is presented in Table 7. The breakdown of each equation into its component cost equations is presented in Table 8, and is discussed in detail in Appendix A. The costs were represented by the equation, $y = KX^a$, where y is the total dollars ($) to supply a given quantity of water, K is the cost coefficient, X is the quantity of water in acre-ft (AF), and a is the economy of scale factor. The values represent the costs of collecting the water from a source or from the effluent of a treatment process, and transporting the water to a destination for use or for treatment to the quality

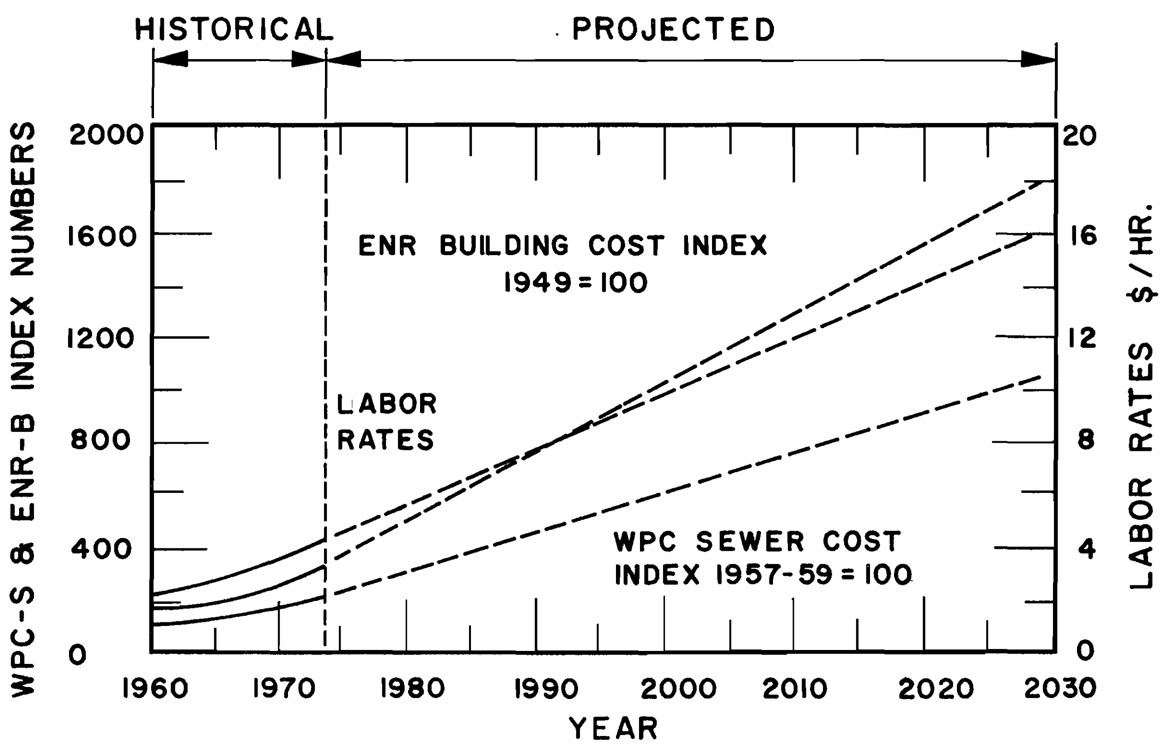


Figure 7. Comparison of cost indices.

Table 6. Cost indices.

Year	Labor[a] Rates $/hr	WPC Construction Cost Index[b] WTP 1957-59[d]	Sewers 1957-59	Engineering New Record Cost Index[c] Building 1913	Building 1949	Construction 1913	Construction 1949
1958	2.00	101.50	100.42	521.09	148.13	757.31	158.77
1959	2.07	103.65	104.78	548.35	155.87	795.16	166.70
1960	2.17	104.96	106.22	561.02	159.48	826.64	173.29
1961	2.27	105.83	108.19	570.17	162.07	850.38	178.28
1962	2.33	106.99	109.72	579.57	164.75	872.90	182.99
1963	2.38	108.52	113.07	589.90	167.69	897.48	188.44
1964	2.44	110.54	115.10	612.22	174.03	935.42	196.09
1965	2.54	112.57	117.31	625.84	177.90	971.14	203.58
1966	2.68	116.92	121.18	656.31	186.56	1028.65	215.64
1967	2.82	120.28	125.36	675.17	191.92	1072.02	224.73
1968	3.00	n.a.[e]	130.50	700.67	199.17	1154.18	241.96
1969	3.24	n.a.	139.78	798.26	226.91	1284.96	269.37
1970	3.52	n.a.	150.93	830.14	235.98	1368.66	286.72
1971	3.74	n.a.	168.36	944.31	268.43	1575.05	330.19
1972	3.97	n.a.	186.91	1048.37	297.83	1760.78	368.35
1973	4.18	n.a.	201.07	1137.76	323.23	1896.13	396.69
1974	4.36	n.a.	211.66	1199.20	340.66	1993.47	417.05

[a]U.S. Labor Statistics Bureau (1974).

[b]Federal Water Pollution Control Administration (1967) and U.S. Department of Commerce (1974).

[c]Engineering New Record (1974).

[d]Year in which cost index equal to 100.

[e]Not available.

indicated. In Table 7 the costs represented by '+' indicate that the path is undesirable, and the costs represented by '0' indicate that the water is of suitable quality to be used directly or discharged directly. The costs shown are for use in one planning area, and it is necessary to add a water transportation cost to use or send the water to another planning area. The detailed discussion of costs, Appendix A, is keyed to the matrix of Table 7. Thus the description is organized to present the costs for each water use section or destination (denoted by the letters A,B, etc.) which can be served from a particular water source or origin (as specified by the number 1, 2, etc.).

Table 7. Total water treatment and reuse cost equation[a], $y = KX^{a}$.

Destinations → / Origins ↓		A Water Treatment Plants	B Municipal Culinary Water	C Industrial Water	D Agricultural Water	E Existing Secondary Treatment	F Wastewater Treatment Level 1	G Wastewater Treatment Level 2	H Wastewater Treatment Level 3	I Wastewater Treatment For Reuse	J Water Fowl Outflow	K System Outflow
1	Surface Water Better Than Class C	$243 X^{0.773}$	$829 X^{0.779}$	$725 X^{0.595}$	$4747 X^{0.31}$	+	+	+	+	+	0	0
2	Water Treatment Plant	+	$81.0 X^{0.90}$	$81.0 X^{0.90}$	$81.0 X^{0.90}$	+	+	+	+	+	+	+
3	Wells	$496 X^{0.714}$	$245 X^{0.842}$	$206 X^{0.768}$	$199 X^{0.75}$	+	+	+	+	+	+	+
4	Municipal Effluent	+	+	+	+	$430 X^{0.853}$	$556 X^{0.847}$	$807 X^{0.821}$	$1387 X^{0.790}$	$1620 X^{0.802}$	+	+
5	Industrial Effluent	+	+	+	+	$459 X^{0.848}$	$583 X^{0.844}$	$836 X^{0.819}$	$1419 X^{0.789}$	$1662 X^{0.800}$	+	+
6	Existing Secondary Treatment	+	+	+	$4747 X^{0.31}$	+	+	$481 X^{0.644}$	$1254 X^{0.674}$	$1199 X^{0.754}$	0	0
7	Wastewater Treatment Level 1	+	+	+	$4747 X^{0.31}$	+	+	$505 X^{0.644}$	$1317 X^{0.674}$	$1259 X^{0.754}$	0	0
8	Wastewater Treatment Level 2	+	+	$1124 X^{0.51}$	$4747 X^{0.31}$	+	+	+	$834 X^{0.686}$	$891 X^{0.774}$	0	0
9	Wastewater Treatment Level 3	$873 X^{0.706}$	+	$1124 X^{0.51}$	$4747 X^{0.31}$	+	+	+	+	$275 X^{0.841}$	0	0
10	Wastewater Treatment for Reuse	+	$81.0 X^{0.90}$	$1124 X^{0.51}$	$4747 X^{0.31}$	+	+	+	+	+	0	0
11	Surface Water Worse Than Class C	$216 X^{0.839}$	$782 X^{0.803}$	$322 X^{0.767}$	$4747 X^{0.31}$	+	+	+	+	+	0	0
12	CUP Jordan Narrows WTP	+	$124 X^{0.962}$	$289 X^{0.866}$	$289 X^{0.866}$	+	+	+	+	+	+	+

[a]Cost equations represent total cost in June, 1974, dollars ($) with X in AF/YR. The + symbol indicates an undesirable use, and was given the value $y = 9999 X^{1.0}$. The 0 symbol indicates a zero (0) cost. Costs are given to go from effluent of origin to effluent of destination.

Table 8. Summary of cost equation[a].

	Destination	Eq	Unit Processes	a Capital	b O & M	c Total
			ORIGIN 1: Surface Water Better Than Class C			
A	Water Treatment Plants	1	Water handling Water collection from river	$10.3\ X^{0.90}$	$24.1\ X^{0.90}$	$34.5\ X^{0.90}$
		2	Water treatment plant Existing	$81.0\ X^{0.67}$	$245\ X^{0.67}$	$326\ X^{0.67}$
		3	Composite cost equation			$243\ X^{0.773}$
B	Municipal Culinary Water	5	Water handling Water collection from river Water distribution	$44.6\ X^{0.90}$	$70.8\ X^{0.90}$	$115\ X^{0.90}$
		6	Water treatment plant New	$256\ X^{0.692}$	$770\ X^{0.692}$	$1026\ X^{0.692}$
		7	Composite cost equation			$829\ X^{0.779}$
C	Industrial Water	10	Water handling Pumpage from river Chlorination	$282\ X^{0.536}$	$475\ X^{0.613}$	$725\ X^{0.595}$
		11	Composite cost equation			$725\ X^{0.595}$
D	Agricultural Water	14	Water handling Diversion structures Canal costs	$2768\ X^{0.32}$	$1972\ X^{0.295}$	$4747\ X^{0.31}$
		15	Composite cost equation			$4747\ X^{0.31}$
			ORIGIN 2: Water Treatment Plants			
B	Municipal Culinary Water	4	Water handling Water distribution	$34.3\ X^{0.90}$	$46.7\ X^{0.90}$	$81.0\ X^{0.90}$
		16	Composite cost equation			$81.0\ X^{0.90}$
C	Industrial Water	4	Water handling Water distribution	$34.3\ X^{0.90}$	$46.7\ X^{0.90}$	$81.0\ X^{0.90}$
		17	Composite cost equation			$81.0\ X^{0.90}$
D	Agricultural Water	4	Water handling Water distribution	$34.3\ X^{0.90}$	$46.7\ X^{0.90}$	$81.0\ X^{0.90}$
		18	Composite cost equation			$81.0\ X^{0.90}$
			ORIGIN 3: Wells			
A	Water Treatment Plants	19	Water handling Well water	$818\ X^{0.453}$	$33.2\ X^{0.90}$	$199\ X^{0.75}$
		2	Water treatment plant Existing	$81.0\ X^{0.67}$	$245\ X^{0.67}$	$326\ X^{0.67}$
		20	Composite cost equation			$496\ X^{0.714}$
B	Municipal Culinary Water	21	Water handling Well water Chlorination Water distribution	$206\ X^{0.753}$	$89.1\ X^{0.90}$	$245\ X^{0.842}$
		22	Composite cost equation			$245\ X^{0.842}$

Table 8. (Continued).

Destination		Eq	Unit Processes	a Capital	b O & M	c Total
C	Industrial Water	23	Water handling Well water Chlorination	$755 X^{0.476}$	$42.4 X^{0.80}$	$206 X^{0.768}$
		24	Composite cost equation			$206 X^{0.768}$
D	Agricultural Water	19	Water handling Well water	$818 X^{0.453}$	$33.2 X^{0.90}$	$199 X^{0.75}$
		25	Composite cost equation			$199 X^{0.75}$
			ORIGIN 4: Municipal Effluents			
E	Existing Secondary Wastewater Treatment Plant	26	Sewage handling Sewage collection	$151 X^{0.91}$	$23.0 X^{0.91}$	$174 X^{0.91}$
		27	Wastewater treatment Existing - Trickling filter	$137 X^{0.784}$	$311 X^{0.668}$	$396 X^{0.732}$
		28	Composite cost equation			$430 X^{0.853}$
F	Wastewater Treatment Plant - Level 1	26	Sewage handling Sewage collection	$151 X^{0.91}$	$23.0 X^{0.91}$	$174 X^{0.91}$
		29	Wastewater treatment New - Activated sludge	$253 X^{0.780}$	$240 X^{0.756}$	$489 X^{0.770}$
		30	Composite cost equation			$556 X^{0.847}$
G	Wastewater Treatment Plant - Level 2	26	Sewage handling Sewage collection	$151 X^{0.91}$	$23.0 X^{0.91}$	$174 X^{0.91}$
		32	Wastewater treatment New - Activated sludge Rapid sand filtration	$325 X^{0.766}$	$555 X^{0.713}$	$855 X^{0.739}$
		33	Composite cost equation			$807 X^{0.821}$
H	Wastewater Treatment Plant - Level 3	26	Sewage handling Sewage collection	$151 X^{0.91}$	$23.0 X^{0.91}$	$174 X^{0.91}$
		35	Wastewater treatment New - Activated sludge Rapid sand filtration Carbon adsorption	$706 X^{0.722}$	$900 X^{0.718}$	$1603 X^{0.720}$
		36	Composite cost equation			$1387 X^{0.790}$
I	Wastewater Treatment Plant For Water Reuse	26	Sewage handling Sewage collection	$151 X^{0.91}$	$23.0 X^{0.91}$	$174 X^{0.91}$
		38	Wastewater treatment New - Activated sludge Rapid sand filtration Carbon Adsorption Ion exchange (33% blend)	$709 X^{0.740}$	$993 X^{0.769}$	$1686 X^{0.759}$
		39	Composite cost equation			$1620 X^{0.802}$

Table 8. (Continued).

Destination		Eq.	Unit Processes	a Capital	b O & M	c Total
			ORIGIN 5: Industrial Effluent			
E	Existing Secondary Wastewater Treatment Plant	41	Sewage handling Pretreatment of sewage Sewage collection	$157 X^{0.907}$	$36.9 X^{0.876}$	$194 X^{0.902}$
		27	Wastewater treatment Existing - Trickling filter	$137 X^{0.784}$	$311 X^{0.668}$	$396 X^{0.732}$
		42	Composite cost equation			$459 X^{0.848}$
F	Wastewater Treatment Plant - Level 1	41	Sewage handling Pretreatment of sewage Sewage collection	$157 X^{0.907}$	$36.9 X^{0.876}$	$194 X^{0.902}$
		29	Wastewater treatment New - Activated sludge	$253 X^{0.780}$	$240 X^{0.756}$	$489 X^{0.77}$
		43	Composite cost equation			$583 X^{0.844}$
G	Wastewater Treatment Plant - Level 2	41	Sewage handling Pretreatment of sewage Sewage collection	$157 X^{0.907}$	$36.9 X^{0.876}$	$194 X^{0.902}$
		32	Wastewater treatment New - Activated sludge Rapid sand filtration	$325 X^{0.766}$	$555 X^{0.713}$	$855 X^{0.739}$
		44	Composite cost equation			$836 X^{0.819}$
H	Wastewater Treatment Plant - Level 3	41	Sewage handling Pretreatment of sewage Sewage collection	$157 X^{0.907}$	$36.9 X^{0.876}$	$194 X^{0.902}$
		35	Wastewater treatment New - Activated sludge Rapid sand filtration Carbon adsorption	$706 X^{0.722}$	$900 X^{0.718}$	$1603 X^{0.720}$
		45	Composite cost equation			$1419 X^{0.789}$
	Wastewater Treatment Plant For Water Reuse	41	Sewage handling Pretreatment of sewage Sewage collection	$157 X^{0.907}$	$36.9 X^{0.876}$	$194 X^{0.902}$
		38	Wastewater treatment New - Activated sludge Rapid sand filtration Carbon adsorption Ion exchange (33% blend)	$709 X^{0.740}$	$993 X^{0.769}$	$1686 X^{0.759}$
		46	Composite cost equation			$1662 X^{0.800}$
			ORIGIN 6: Existing Secondary Wastewater Treatment Plants			
D	Agricultural Water	14	Water handling Diversion structures Canal costs	$2768 X^{0.32}$	$1972 X^{0.295}$	$4747 X^{0.31}$
		47	Composite cost equation			$4747 X^{0.31}$
G	Wastewater Treatment Level 2	48	Tertiary treatment New - Rapid sand filtration	$95.0 X^{0.662}$	$390 X^{0.638}$	$481 X^{0.644}$
		49	Composite cost equation			$481 X^{0.644}$

Table 8. (Continued).

	Destination	Eq	Unit Processes	a Capital	b O & M	c Total
H	Wastewater Treatment Level 3	50	Tertiary treatment New - Rapid sand filtration Carbon adsorption	$607\ X^{0.633}$	$694\ X^{0.694}$	$1254\ X^{0.674}$
		51	Composite cost equation			$1254\ X^{0.674}$
I	Wastewater Treatment For Water Reuse	52	Tertiary treatment New - Rapid sand filtration Carbon adsorption Ion exchange (33% blend)	$502\ X^{0.698}$	$753\ X^{0.733}$	$1199\ X^{0.754}$
		53	Composite cost equation			$1199\ X^{0.754}$
			ORIGIN 7: Wastewater Treatment - Level 1			
D	Agricultural Water	14	Water handling Diversion structures Canal costs	$2768\ X^{0.32}$	$1972\ X^{0.295}$	$4747\ X^{0.31}$
		54	Composite cost equation			$4747\ X^{0.31}$
G	Wastewater Treatment Level 2	55	Tertiary treatment addition New - Rapid sand filtration	$99.8\ X^{0.662}$	$410\ X^{0.638}$	$505\ X^{0.644}$
		56	Composite cost equation			$505\ X^{0.644}$
H	Wastewater Treatment Level 3	58	Tertiary treatment addition New - Rapid sand filtration Carbon adsorption	$637\ X^{0.633}$	$729\ X^{0.694}$	$1317\ X^{0.674}$
		59	Composite cost equation			$1317\ X^{0.674}$
I	Wastewater Treatment For Water Reuse	61	Tertiary treatment addition New - Rapid sand filtration Carbon adsorption Ion exchange	$527\ X^{0.698}$	$791\ X^{0.773}$	$1259\ X^{0.754}$
		62	Composite cost equation			$1259\ X^{0.754}$
			ORIGIN 8: Wastewater Treatment - Level 2			
C	Industrial Water	8	Water handling Water pumping	$292\ X^{0.51}$	$832\ X^{0.51}$	$1124\ X^{0.51}$
		63	Composite cost equation			$1124\ X^{0.51}$
D	Agricultural Water	14	Water handling Diversion structures Canal costs	$2768\ X^{0.32}$	$1972\ X^{0.295}$	$4747\ X^{0.31}$
		64	Composite cost equation			$4747\ X^{0.31}$
H	Wastewater Treatment Level 3	57	Tertiary treatment addition New - Carbon adsorption	$541\ X^{0.626}$	$366\ X^{0.724}$	$834\ X^{0.686}$
		65	Composite cost equation			$834\ X^{0.686}$
I	Wastewater Treatment For Water Reuse	66	Tertiary treatment addition New - Carbon adsorption Ion exchange (33% blend)	$434\ X^{0.703}$	$526\ X^{0.799}$	$891\ X^{0.774}$
		67	Composite cost equation			$891\ X^{0.774}$

Table 8. (Continued).

Destination		Eq	Unit Processes	a Capital	b O & M	c Total
			ORIGIN 9: Wastewater Treatment - Level 3			
A	Water Treatment Plants	70	Water handling Water transmission	$1544\ X^{0.535}$	$179\ X^{0.822}$	$873\ X^{0.706}$
		71	Composite cost equation			$873\ X^{0.706}$
C	Industrial Water	8	Water handling Water pumping	$292\ X^{0.51}$	$832\ X^{0.51}$	$1124\ X^{0.51}$
		72	Composite cost equation			$1124\ X^{0.51}$
D	Agricultural Water	14	Water handling Diversion structures Canal costs	$2768\ X^{0.32}$	$1972\ X^{0.295}$	$4747\ X^{0.31}$
		73	Composite cost equation			$4747\ X^{0.31}$
I	Wastewater Treatment For Water Reuse	74	Tertiary treatment addition New - Ion exchange (33% blend)	$44.8\ X^{0.841}$	$230\ X^{0.841}$	$275\ X^{0.841}$
		75	Composite cost equation			$275\ X^{0.841}$
			ORIGIN 10: Wastewater Treatment - For Water Reuse			
B	Municipal Culinary Water	4	Water handling Water distribution	$34.3\ X^{0.90}$	$46.7\ X^{0.90}$	$81.0\ X^{0.90}$
		76	Composite cost equation			$81.0\ X^{0.90}$
C	Industrial Water	8	Water handling Water pumping	$292\ X^{0.51}$	$832\ X^{0.51}$	$1124\ X^{0.51}$
		77	Composite cost equation			$1124\ X^{0.51}$
D	Agricultural Water	14	Water handling Diversion structure Canal costs	$2768\ X^{0.32}$	$1972\ X^{0.295}$	$4747\ X^{0.31}$
		78	Composite cost equation			$4747\ X^{0.31}$
			ORIGIN 11: Surface Water Worse Than Class C			
A	Water Treatment Plant	80	Water handling Water collection from river Water pretreatment	$20.4\ X^{0.90}$	$41.0\ X^{0.941}$	$60.9\ X^{0.930}$
		2	Water treatment plant Existing	$81.0\ X^{0.67}$	$245\ X^{0.67}$	$326\ X^{0.67}$
		81	Composite cost equation			$216\ X^{0.839}$
B	Municipal Culinary Water	82	Water handling Water collection from river Water pretreatment Water distribution	$54.8\ X^{0.90}$	$86.3\ X^{0.923}$	$141\ X^{0.915}$
		6	Water treatment plant New	$256\ X^{0.692}$	$770\ X^{0.692}$	$1026\ X^{0.692}$
		83	Composite cost equation			$782\ X^{0.803}$

Table 8. (Continued).

	Destination	Eq	Unit Processes	Capital[a]	O & M[b]	Total[c]
C	Industrial Water	85	Water handling Pumpage from river Water pretreatment Chlorination	$124 X^{0.708}$	$212 X^{0.785}$	$322 X^{0.767}$
		86	Composite cost equation			$322 X^{0.767}$
D	Agricultural Water	14	Water handling Diversion structure Canal costs	$2768 X^{0.32}$	$1972 X^{0.295}$	$4747 X^{0.31}$
		87	Composite cost equation			$4747 X^{0.31}$
		ORIGIN	12: Central Utah Project - Jordan Narrows Water Treatment Plant			
B	Municipal Culinary Water	89	Water handling Purchase price Water distribution	$56.5 X^{0.966}$	$67.6 X^{0.959}$	$124 X^{0.962}$
		90	Composite cost equation			$124 X^{0.962}$
C	Industrial Water	92	Water handling Purchase price Pumping	$95.8 X^{0.90}$	$203 X^{0.838}$	$289 X^{0.866}$
		93	Composite cost equation			$289 X^{0.866}$
D	Agricultural Water	92	Water handling Purchase price Pumping	$95.8 X^{0.90}$	$203 X^{0.838}$	$289 X^{0.866}$
		94	Composite cost equation			$289 X^{0.866}$

[a]Cost equations represent component costs in June 1974, dollars ($) with X in AF/YR.

CHAPTER IV

MODEL OPERATION AND COMPARISON OF RESULTS

Comparative Analysis of Model Runs

The basic model employed for the study can be structured with varying complexity from a simple model consisting of a grouped sectoral division of users and aggregated sources to a highly complex model incorporating finely divided users, based on spatial, temporal, and water quality aspects, and segregated sources. The larger and more complex the model, the higher the cost of solution in terms of computer time, disk storage, and the labor involved in data analysis and model structuring. But the information that can be gained may also increase because a complex model involves less of abstraction from the real world.

In this chapter a number of optimal solutions for different model structures are analyzed in order to compare the costs and the amount of relevant information each yields. The results of various model structures are discussed under the following headings:

1. Spatial aggregation versus disaggregation

2. Imposition of higher wastewater treatment levels

3. Annual versus seasonal variations

4. Linear versus nonlinear costs

5. Deterministic versus stochastic supplies

Table 9 is constructed to indicate model runs referred to in Table 1 from which the comparisons of results are derived. The x's linked by the dotted lines in the table indicate the pairs of runs from which the comparisons are drawn.

The comparisons of results in the following sections are meant to be only illustrative examples of the types of information that can be derived from the various model structures rather than complete detailed comparisons and analyses. The discussion, however, does indicate generally what information can be gained through higher levels of detail or resolution in the models.

Analysis of Results for Model Structures

Spatial aggregation versus disaggregation

The aggregated model was constructed for two purposes. The first was to reduce the computer time cost for nonlinear study; and the second was to study the feasibility of a regional wastewater

Table 9. Runs used for comparison of results for various model structures.

	Runs (Table 1)							
Comparisons	1	2	3	4	5	6	7	8
1. Spatial		x--------	--------x					
2. Treatment			x--------	--------x	x--------	--------x	x--------	--------x
3. Annual/Seasonal			x--------	--------	--------x			
				x--------	--------	--------x		
4. Linear/Nonlinear	x--------	--------x						
5. Deter./Stochastic			x--------	--------	--------	--------	--------x	
				x--------	--------	--------	--------	--------x

treatment plant in the area and the implementation of higher effluent standards. In aggregating from the spatial resolution existing in the seven subregions model, the wastewater treatment plants were combined into a single facility for each aggregated subregion. Further, the transportation distance from municipal and industrial centers to any combined facility was averaged. Hence, the operational capacity of any individual plant was not specified, and only combined plant capacity for subregions was used.

The capacity allocation for wastewater treatment facilities in 2020 is used as an example for comparison. The seven subregions model shows how each wastewater treatment plant in each subregion is operated (Figure 8). Wastewater

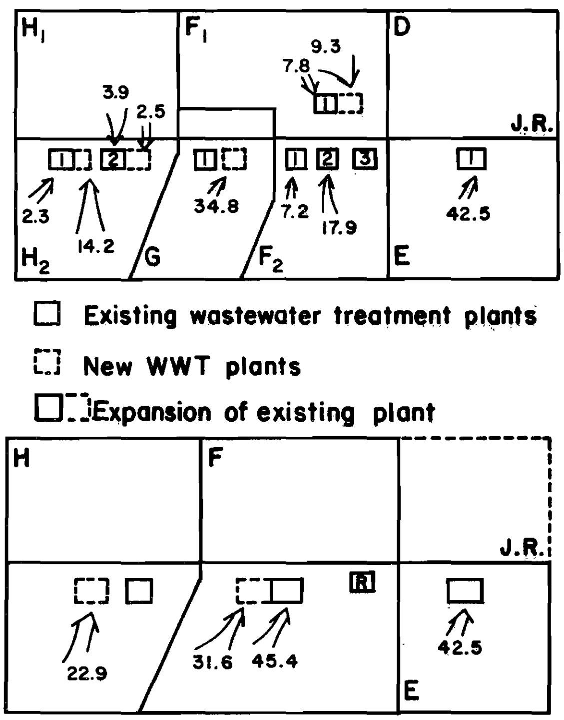


Figure 8. WWTP utilization in 2020 under existing water quality standard.

treatment plant 3 in subregion F_2 is idle; a new wastewater treatment plant is preferred in subregion G, and additional capacity is needed for wastewater treatment plants in H_2 and F_1. The only subregion with adequate capacity is E. In the aggregated model, the combined existing wastewater treatment plant capacity in subregion F is exhausted and expansion of capacity is required. However, the expansion capacity requirement for aggregated subregion F is less than the individual subregions composite by the amount equal to the idle WWT 3 in subregion F_2. In subregion H a new treatment plant is preferred, instead of expanding the existing facility.

Effect of higher discharge quality requirements

The transportation structure for modeling a regional water resources system yields an integrated approach to water and wastewater management (Bishop et al., 1974). The imposition of water quality standards indicates that poor effluent quality is an externality in that the discharger pays only his private costs while the downstream user has to pay both his private cost and the cost of reduced quality. This divergence between the social and private costs clearly leads to market failure and a loss of economic efficiency. On the other hand, the effluent is a water resource and therefore a positive resource value may be attributed if costs are less than revenues generated. Until reuse is economically feasible, the effluent is a cost. Therefore, the effect of imposition of water quality requirements is analyzed in the following ways:

(1) By either changing the costs (in a model where higher treatment levels are not explicitly introduced as in the seven-region model), or (2) by changing the right hand elements for treatment plants (in a model where higher treatment levels are explicitly introduced as in the aggregate model).

A higher quality effluent standard means additional treatment is required before the effluent can be discharged into a receiving water body, implying that the existing treatment plant has to be upgraded to meet the quality standard. However, higher effluent quality offers higher potential for reuse. In general, higher quality effluent for reuse replaces groundwater use in industrial sectors. Reuse in agricultural sectors increases if alternative sources become less dependable and imported water is insufficient. Seasonal variation has little impact on reuse.

The effect of higher standards which require secondary treatment (Level II) before 1980 and tertiary treatment (Level III) before 1985 is illustrated in Figures 9 through 12. The 1980 requirement is met by adding Level II treatment in the regions. For the 1985 Level III the optimal solution indicates a large regional plant serving areas E and F and further expansion of facilities to Level III in H. This pattern continues through 2020.

Imposing higher standards on effluent discharge results in higher cost for an optimal allocation (see Table 10 and Figure 13). The additional cost is due mainly to additional treatment requirement. Reuse activities in the system do not increase even though higher quality effluent is available (compare Figure 10 and 12).

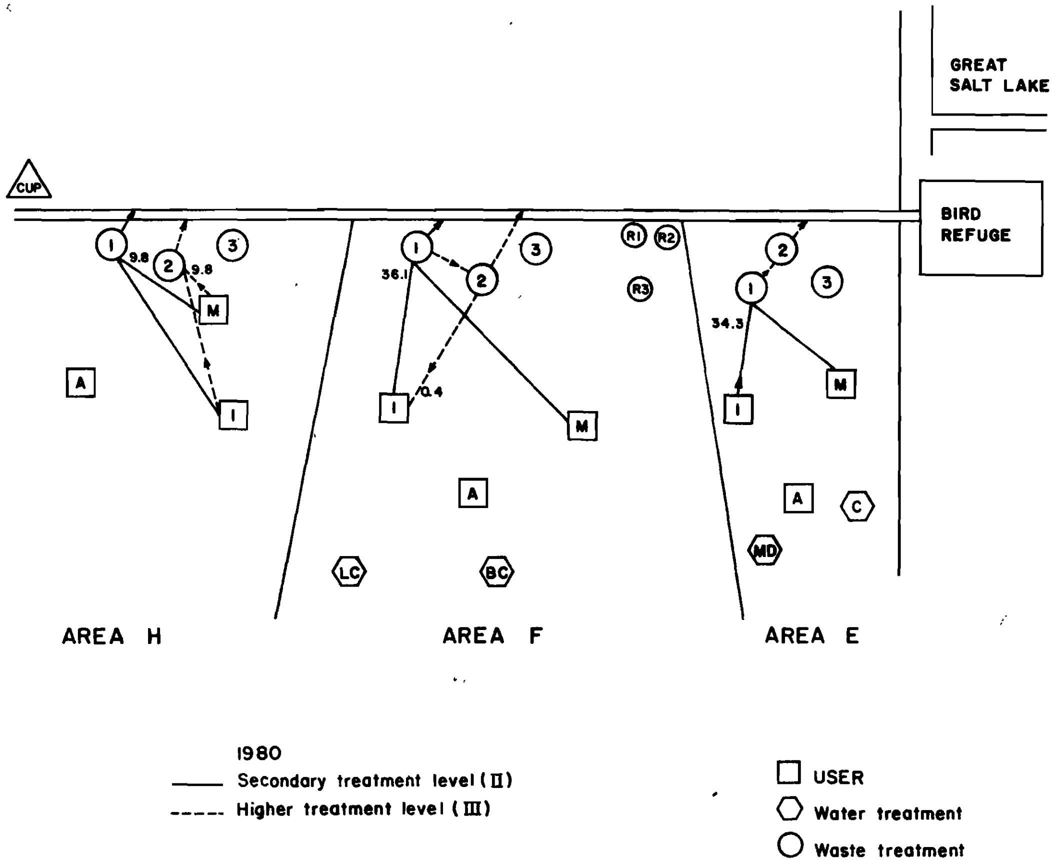


Figure 9. Wastewater and water reuse flows resulting from higher level treatment requirements, 1980.

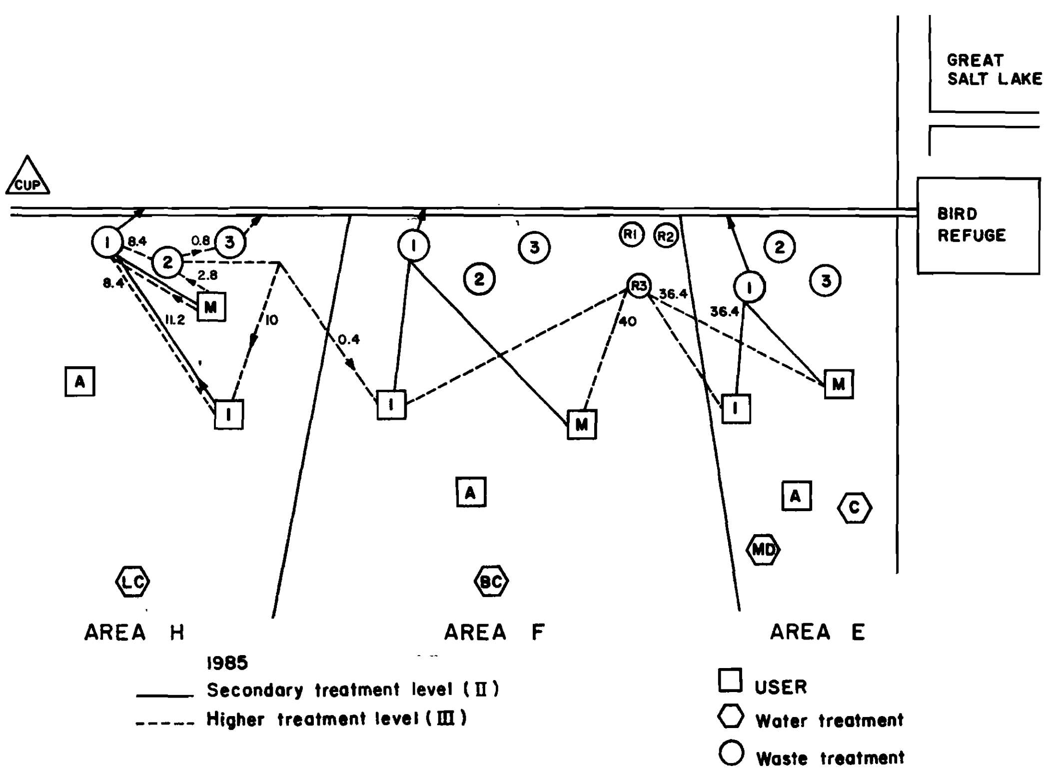


Figure 10. Wastewater and water reuse flows resulting from higher level treatment requirements, 1985.

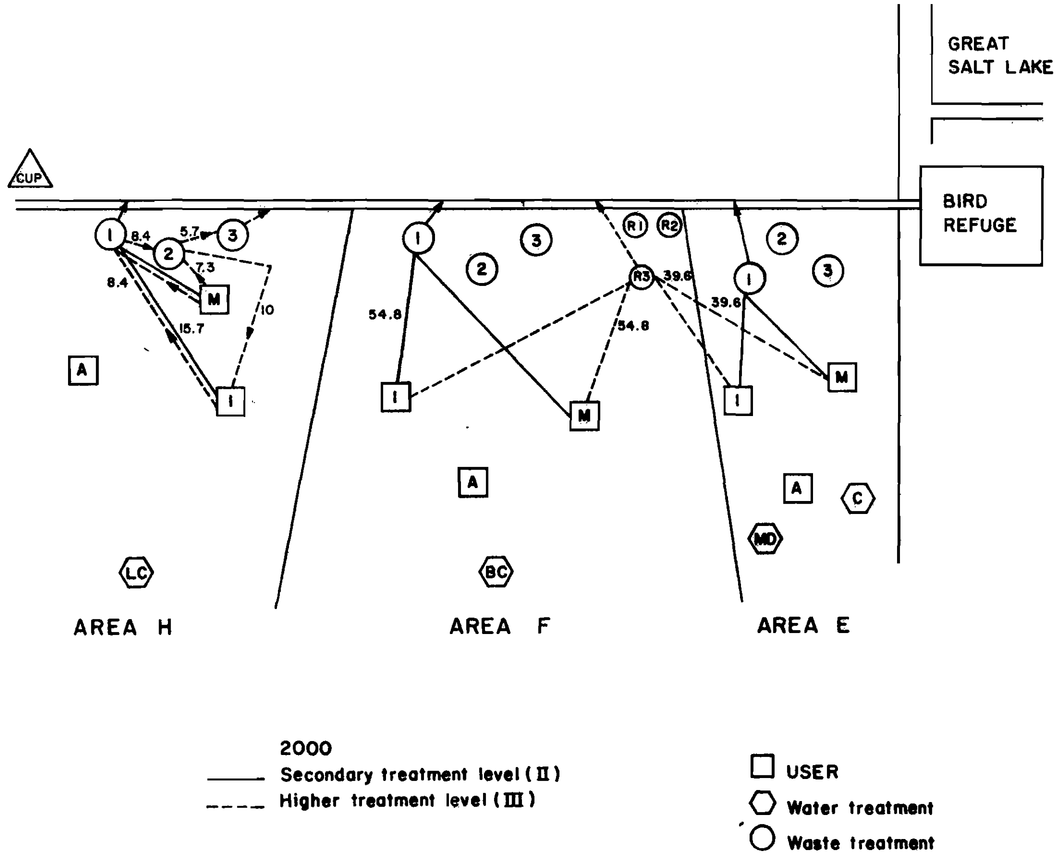


Figure 11. Wastewater and water reuse flows resulting from higher level treatment requirements, 2000.

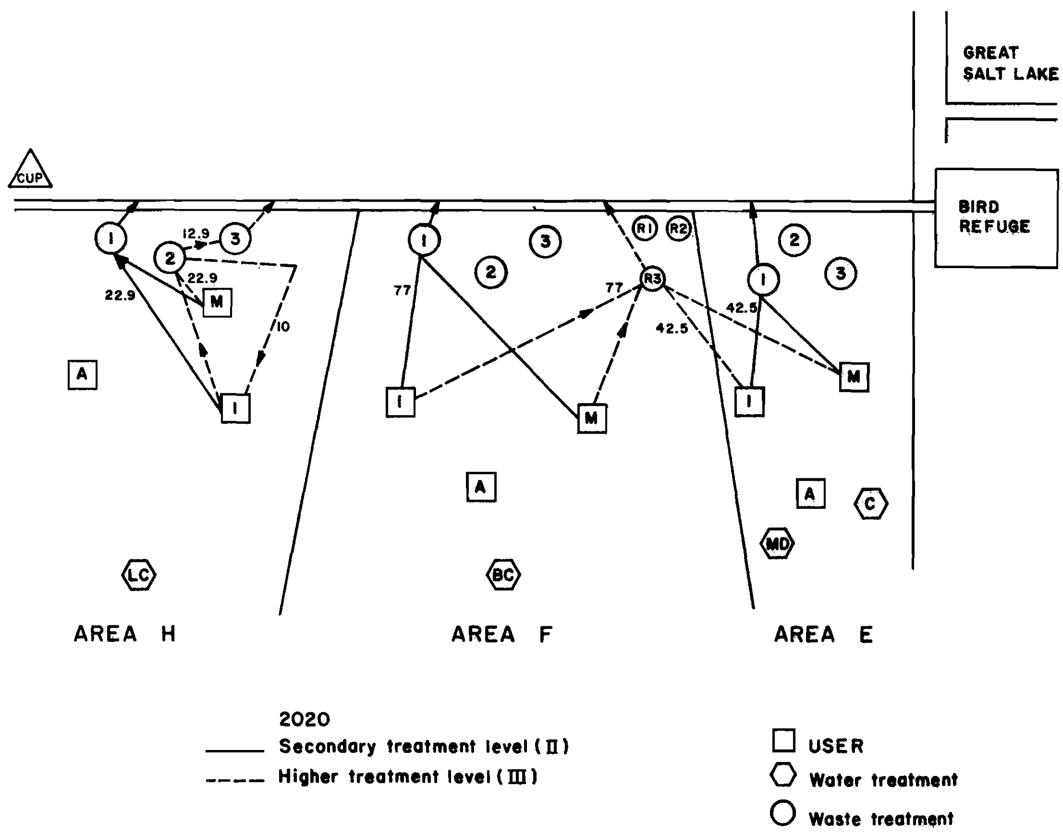


Figure 12. Wastewater and water reuse flows resulting from higher level treatment requirements, 2020.

Table 10. Annual cost comparison of optimal allocations.

	Allocation	1975	1980	1985	2000	2020
(a)	III deterministic	13.42[a]	15.09	16.47	21.00	26.80
	IV deterministic		16.25	21.32	26.31	32.55
(b)	VII stochastic	13.57	15.13	16.54	21.06	27.65
	VIII stochastic		16.23	22.00	26.76	33.61
(c)	V	13.17	14.42	15.62	19.28	26.18
	VI		15.60	20.07	24.20	31.91

[a]Cost of allocation in million dollars.

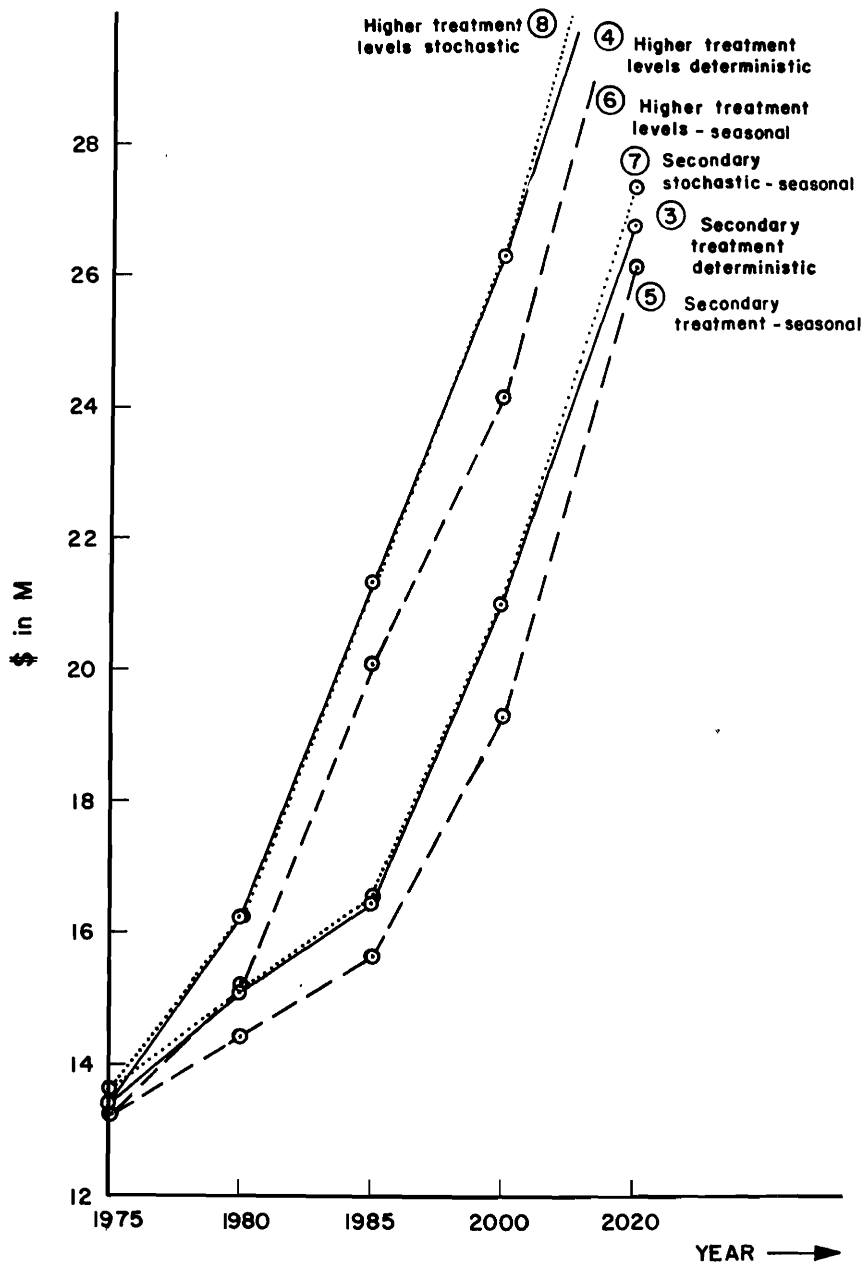


Figure 13. Comparison of total minimum cost of optimal allocation under various model assumptions.

It is recognized that the use of average annual values in the model yields estimates of capacity expansion schemes for treatment facilities in the region that may not be adequate to meet peak demand situations. The water availabilities and usage patterns fluctuate considerably over time and unless the fluctuations are taken into account, required capacities of the treatment facilities could be understated by the model. While peak demand problems were not explicitly considered in this analyses, peak factors could be applied to effluent flows to further study this aspect.

Seasonal variations

It is entirely possible that seasonal changes in supply and water requirements could substantially change allocation patterns and the total system cost. Seasonality was analyzed by solving the model for summer and winter months separately. A biseasonal year was used in order to reduce the cost of computer runs, since a finer subdivision (a monthly or a four-season model) involves considerably more computational effort. The water flow and usage in the study area generally were found to sharply deviate only with respect to summer and winter months, and appeared to be relatively stable over the two seasons, although no statistical analysis was undertaken.

The seasonal variation or supply and requirements in the study area has two pronounced effects on allocation: First, the capacity requirements for water treatment plants and wastewater treatment plant changes; and second, the overall reuse pattern in agricultural sectors changes where the seasonal variation in the system restricts irrigation reuse during winter months but not during summer months.

The municipal requirements are higher during summer months and the existing water treatment plant capacity may need to be expanded to satisfy the municipal requirements by the 2020 if the existing use patterns persist. On the other hand, wastewater treatment plant capacity requirements are generally less than the corresponding annual capacity requirement. During summer months when large volumes of effluent occur, reuse opportunity, especially in agricultural sectors, is also at maximum, and a large volume of effluent is diverted for reuse. Thus, the capacity requirements for a wastewater treatment plant during summer months is less than the corresponding winter months.

The seasonal total allocation cost indicates savings in the system over annual allocation (Figure 14). The apparent savings come from higher reuse activities, especially in irrigation, and the concomitant reduced waste treatment capacity requirements.

Linear vs. nonlinear cost function

The use of nonlinear cost functions introduces economies of scale. The nonlinearity has a pronounced effect on imported water volume. Small amounts of imported water are comparatively expensive but large volumes become competitive due to large economies of scale in the conveying system. The economies of scale for treatment plants as compared to the interregional transportation cost will have considerable effect on decisions about expanding the wastewater treatment facilities or transporting effluent to nearby treatment plants. The nonlinear cost formulation forces trade-off decisions at all times, depending on the excess volume of the effluent. The allocation cost obtained from nonlinear solution should reflect a more realistic estimated cost than the average cost solution.

Comparison of wastewater treatment plant utilization in the case of linear and nonlinear models is interesting. Data used in the following analysis pertain to seven-region model results. In subregions where the wastewater treatment plant capacity is not exceeded, allocations for the linear and nonlinear cost model are identical. However, where the subregion wastewater treatment plant's capacity is exceeded, there is significant difference in allocation. The linear solution generally indicates transportation of the excess waste to the nearby subregional treatment plants until their capacity is also exceeded; then a new plant in the subregion is preferred (Table 11, subregion G). The nonlinear solution generally indicates a new plant to handle the excess wastewater load. The difference in allocation can be explained in terms of trading off the transportation cost and the new treatment plant cost. In the linear solution where transportation cost and treatment cost per unit are constant throughout, once transportation is preferred over new treatment plant, this decision will hold through a range of allocations. However, the nonlinear solution has to compare transportation versus a new plant throughout the range. For example, small excess over capacity in area F1 is treated by a new treatment plant (allocation-1980). As the excess volume significantly increases, the excess is transported to nearby subregional (E) treatment plants instead. For the same reason, TP3 in area F2 is not utilized in nonlinear solution, and the excess waste volume in subarea G is treated by the new treatment plant in that subregion.

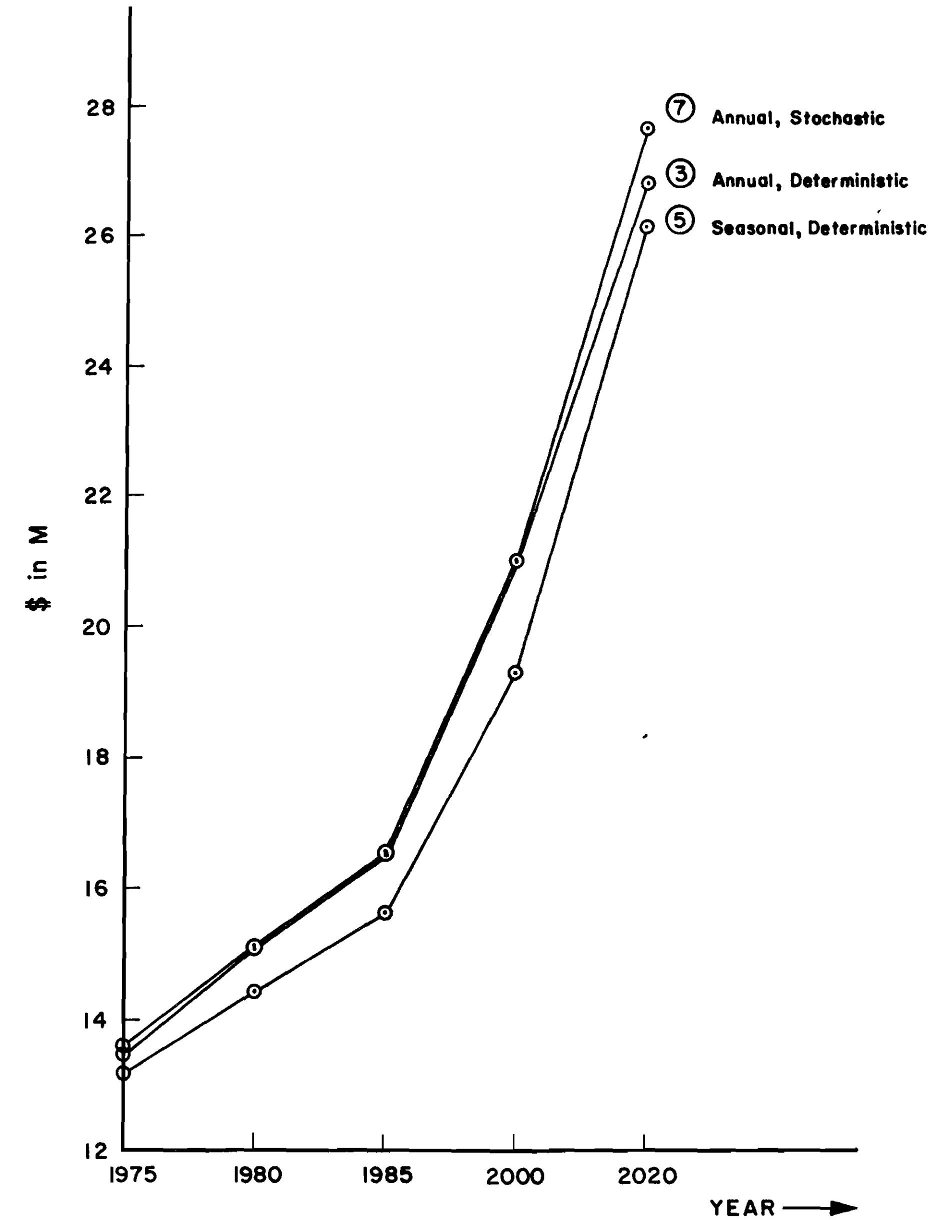


Figure 14. Comparison of total minimum cost of optimal allocation for annual versus seasonal model runs.

Deterministic vs. stochastic models

The aggregate deterministic model assumes that the surface water sources provide an annual flow equal to the average value of their longterm records so that randomness of inflows is not taken into account. However, the stochastic nature of these flows can be characterized by a normal density function and considered by use of the chance-constrained programming approach, which prescribes that the total allocation be less than the availability 95 percent of the time.

The basic model is quite adaptable to both deterministic and stochastic formulations and lends itself to easy solution procedures. The allocation pattern under the latter scheme differs in

Table 11. Wastewater treatment plants utilization.

Areas / Year	Model	H2 TP1	H2 TP2	G TP1	F2 TP1	F2 TP2	F2 TP3	F1 TP1	E TP1	D TP1
1975	Linear	4.5	2.3	5.6	6.0	12.7	0	7.1	33.0	1.5 (81.7)
	NLR	4.5	2.3	5.6 (5.7)	9.0	4.0	0	7.1	33.0	1.4 (81.8)
1980	LR	4.5	3.9	5.6	8.0	14.2	0	7.8	34.8	1.5 (81.8)
	NLR	4.5	3.4	5.6 (7.7)	9.0	5.5	0	7.8 (.5)	34.3	1.5 (81.8)
1985	LR	4.5	3.9	5.6	9.0	16.2	0	7.8	37.8	1.5 (82.1)
	NLR	4.5	3.9	(15.1)	9.0	6.7	0	7.8	36.4	1.5 (82.1)
2000	LR	4.5	3.9	5.6	9.0	17.9	5.1	7.8	44.3	1.5 (82.6)
	NLR	4.5	3.9	(22.5)	9.0	10.8	0	7.8	39.6	1.5 (82.6)
2020	LR	4.5	3.9	5.6	9.0	17.9	5.1	7.8	50.4	1.5 (83.3)
	NLR	2.3	3.9	(34.8)	7.2	17.9	0	7.8	42.5	1.5 (83.3)

The quantities in parentheses indicate additional treatment capacity necessary in the respective subregions.

that the more dependable sources are substituted in place of the variable surface water. In the optimal solutions, surface water is replaced by imported water, which is assumed to be a more reliable source than surface water over time (Table 12).

The system effects on wastewater treatment and reuse are displayed by Figures 15 through 19. As the diagrams shows reuse is required in area H for industrial purposes over the entire planning horizon. Areas E and F show reuse for 1980 at Level II treatment, but with the Level III regional plant in 1985 reuse is curtailed.

Introduction of stochastic elements into the allocation scheme results in a slight increase of the total allocation cost (lines III and VII, and IV and VIII in Table 10). The increased additional cost comes from additional high cost imported water required by the system. Reuse acitivites increase in the stochastic model only if imported water is insufficient (Figures 15 through 19).

Table 12. Replacement of surface water by import water in optimal solutions for stochastic model.

Year	Surface Water for M&I / Water for M&I	Sw for M&I / Iw for M&I	Sw for Ag / Iw for Ag	Sw for Ag / Iw for Ag
1975	31 /20.2	25.8/25.4	71.3/ 2.9	14.6/59.6
1980	42.2/20.9	40.4/22.7	63.1/ 2.2	0 /65.6
1985	52.5/21.7	40.4/35.5	60 / 2.2	0 /63.2
2000	72 /48.7	36.2/84.5	40.5/ 1.7	0 /43.2
2020	87.7/84.5	40.4/84.5	24.8/ 1.2	0 /27

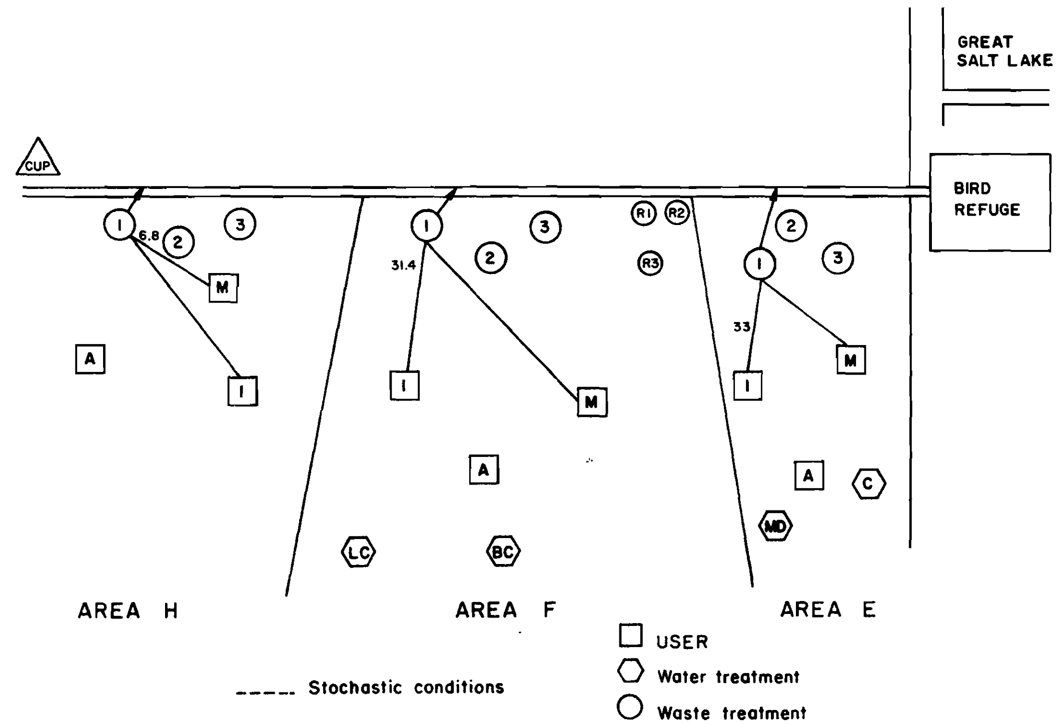


Figure 15. Waste treatment utilization and reuse pattern for 1975 with quality level I.

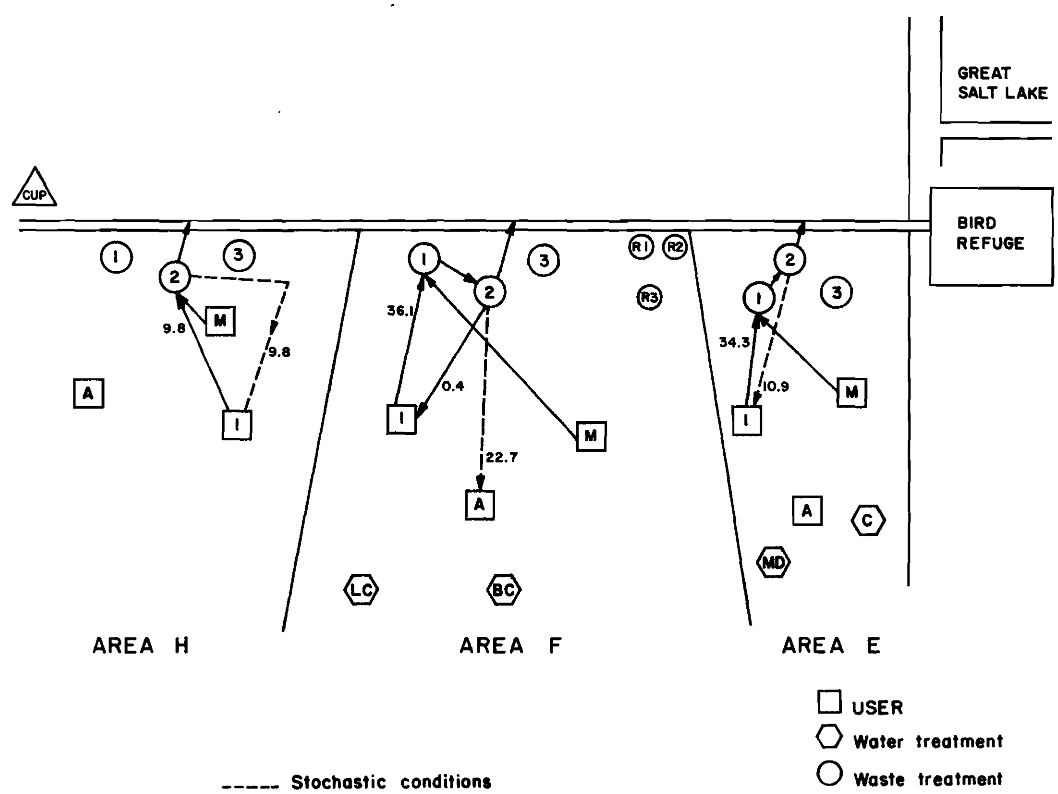


Figure 16. Waste treatment utilization and reuse pattern for 1980 with quality level II.

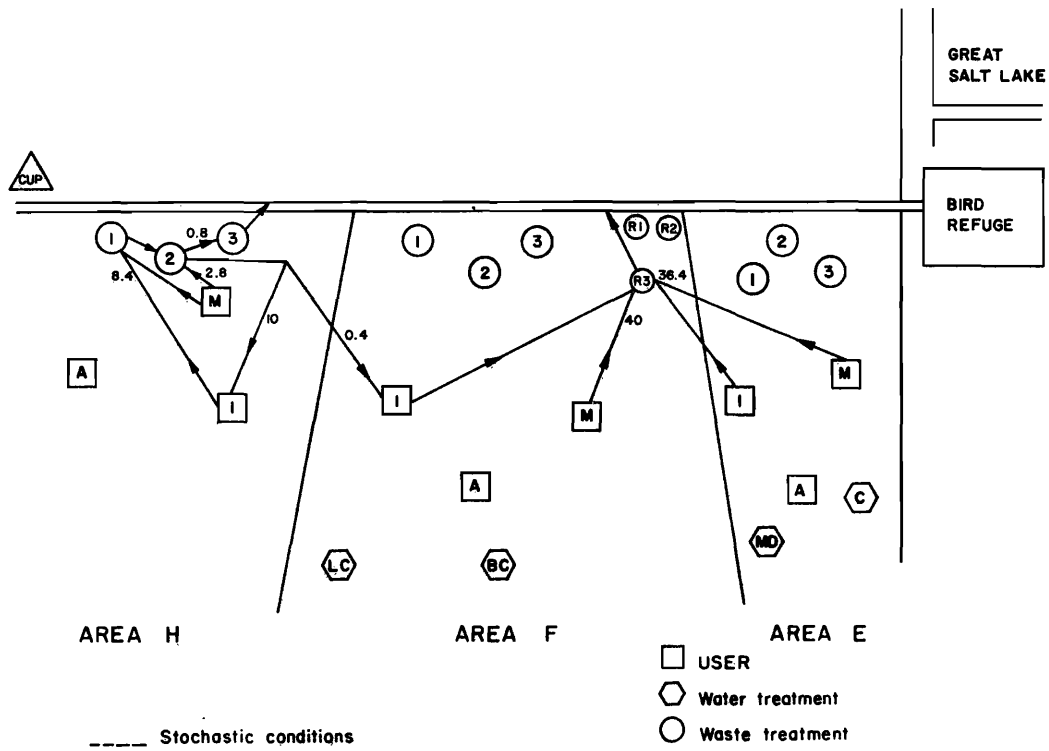


Figure 17. Waste treatment utilization and reuse pattern for 1985 with quality level III.

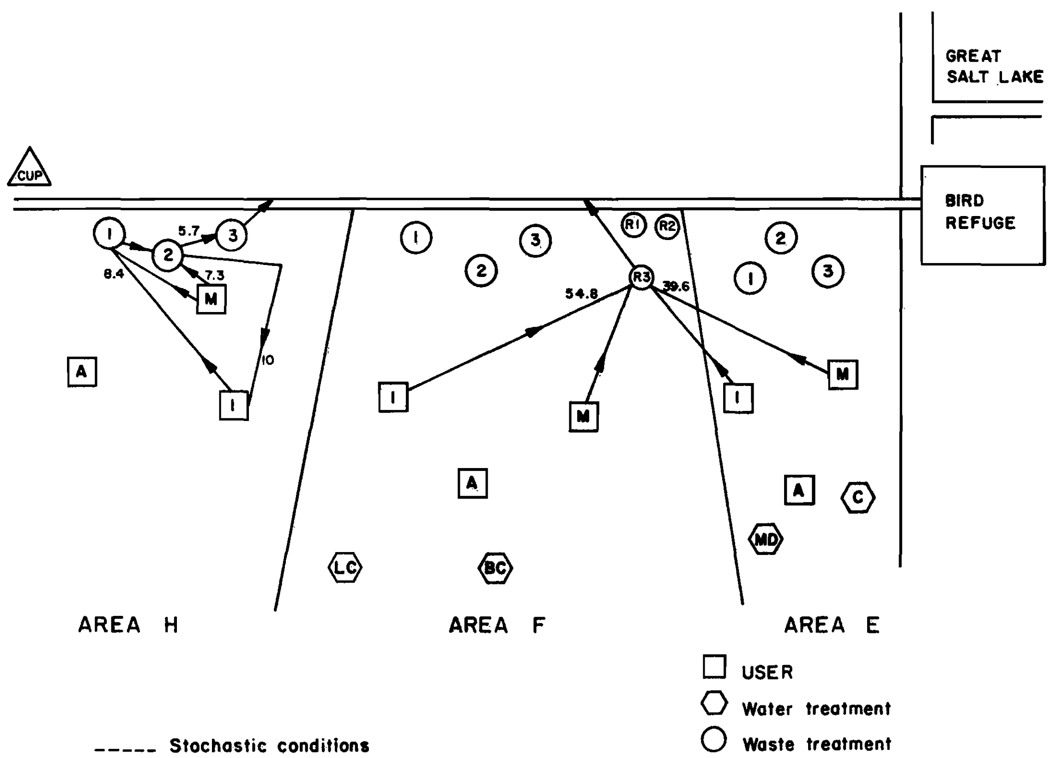


Figure 18. Waste treatment utilization and reuse pattern in 2000 with quality level III.

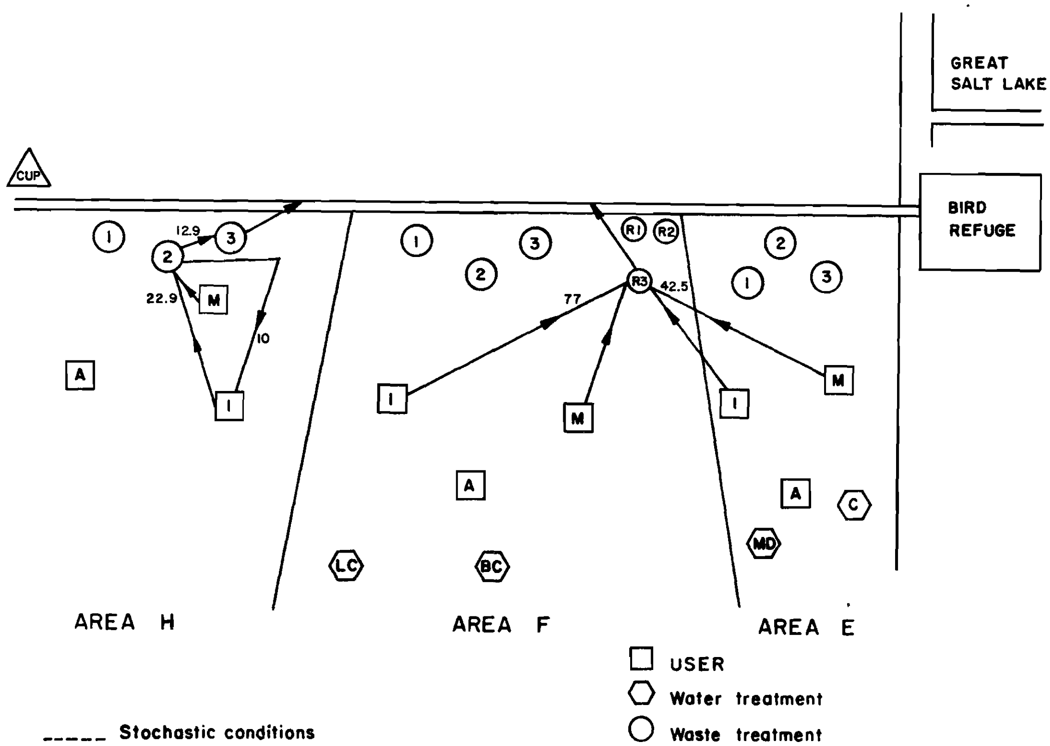


Figure 19. Waste treatment utilization and reuse pattern for 2020 with quality level III.

Sector allocations under various assumptions

As further illustrations of the types of information that might be derived from various model formulations and model runs, the following paragraphs analyze model results for the major water source, water use and treatment sectors in the model.

Surface water and water treatment plants

Model results based on annual average flows and requirements follows findings (Bishop et al., 1974) that water treatment plants in the basin presently have the capacity to meet the requirements for water over the projected study period. However, for high demand periods such as summer months (see Table 13), the existing maximum capacity cannot meet the requirements after 2000.

Groundwater

Groundwater is allocated largely to municipal requirements and very little groundwater is used for other purposes (Table 14). The agricultural sector generally is not allocated any groundwater. Allocation of groundwater in industrial sectors frequently has been replaced by reuse of higher quality effluent, when available. Use of groundwater is increased if dependability of surface water sources is reduced. The utilization of groundwater is increased until the safe yield is reached (103,800 ac-ft/year for aggregated model area of study). Seasonal requirements have very little effect upon allocation or use of goundwater.

Table 13. Water treatment plants (maximum capacity 209,700 ac-ft/year).

Year	Annual Requirement[a]	Summer Requirement[b]
1975	30,600	82,800
1980	41,800	101,600
1985	54,200	117,400
2000	98,300	179,400
2020	147,600	266,000[a]

[a] In ac-ft/year

[b] Adjusted to ac-ft/year.

Reusable sources

The sources available for direct reuse are municipal and industrial effluents. In this study, direct reuse of effluent in the municipal sector is

Table 14. Groundwater withdrawal pattern.

Year		Municipal	Industrial
1975	WQ det	95,800[a]	---
	L1 sto		
1980	WQ det	101,800	---
	L2 sto	101,800	200
1985	WQ det	103,800	---
	L3 sto	33,100	400
2000	WQ det	103,800	---
	L3 sto	77,200	400
2020	WQ det	103,800	---
	L3 sto	103,800	---

[a]In ac-ft/year.
WQ - with secondary treatment
L1, L2, L3 - higher treatment levels 1, 2, and 3
det - deterministic
sto - stochastic

restricted so that the effluent, after first being treated to acceptable standards, can be recycled to water treatment plants.

Figures 9 to 12 showed a comparison and amount of reuse under various assumptions. For existing water quality standards, most of the effluent is discharged to satisfy the bird refuge requirement. If water quality standards are higher, reuse activities are generally confined to industrial sectors. Only under severe shortage (e.g., stochastic 1980) is reuse extended to agricultural sectors (Table 15). Industrial reuse is usually located in subregion H.

Table 15. Reuse pattern: deterministic and stochastic.

Year		Existing		Higher	
		I	A	I	A
1975	annual	0	0	0	0
	seasonal	0	0	0	0
1980	annual	0	0	0.4[a](21.1)	-(22.7)
	seasonal	0	0	1.2	-
1985	annual	0	0	10.4(10.0)	0
	seasonal	0	0	7.1	0
2000	annual	0	0	10.0(10.0)	0
	seasonal	0	0	9.0	0
2020	annual	0	0	10.0(10.0)	0
	seasonal	0	0	10.0	0

[a]The quantities are in thousand ac-ft/year. The quantities in parentheses indicate solution under stochastic conditions.

Imported water

The aggregated model has been structured to allow for water import into the study area. Two import sources, the Salt Lake aqueduct and Central Utah Project, are of quality better than class C, and the Provo Reservoir Canal and Utah Lake Distribution Canal are of quality less than class C. Given the existing cost structure, imported water could be economically competitive to surface water. Usage of imported water better than class C alleviates the problem of shortage of supply in the study area (Table 16). The availability of such imported water will reduce the amount of reuse activities (Figures 9 and 12). Water quality of effluent has very little effect to amount of imported water under the existing cost structure. Water is initially imported for industrial purposes; percentages of industrial uses decrease, even though the actual amount used does not decrease. With severe water shortage, water is shifted to satisfy municipal requirements.

Table 16. Import water better than Class C(ac-ft/year).

Year	Deterministic	Stochastic
1975	20,200 (20,200)[a]	25,400 (20,600)
1980	20,900 (20,900)	22,700 (21,300)
1985	23,400 (21,700)	35,900 (21,700)
2000	48,700 (22,400)	84,500 (22,000)
2020	84,500 (24,600)	84,500 (0)

[a]Industrial use.

Reuse patterns and imported water

Requirements in the study area can be satisfied by additional imported water or reuse of the treated effluent. Generally, where imported water is insufficient, reuse volume is increased. However, at sufficiently high volume, imported water has an advantage over reuse, due to economies of scale (see Tables 17 and 18).

Reuse of reclaimed wastewater based on unit cost starts by the year 1985, in the linear model and later than 2000 in the nonlinear model. Reuse by agriculture is suggested correctly by the linear solution, and after 1985 by the nonlinear solution.

Imported water, especially from CUP, is feasible by the available date in the nonlinear solution. The amount of increased import reduces reuse by approximately the same amount.

Table 17. Reuse comparisons: Linear vs. nonlinear model, municipal and industrial effluent for M, I, and agricultural uses.

Year	M & I Uses		Agricultural Uses	
	Linear	Nonlinear	Linear	Nonlinear
1975	0[a]	0	7,000	0
1980	0	0	5,900	0
1985	2,120	0	5,180	1,400
2000	15,320	0	4,700	4,700
2020	22,900	14,200	14,800	9,300

[a] All figures in acre-feet.

Table 18. Import water comparisons between linear and nonlinear models (municipal use).

Year	Linear	Nonlinear
1975	14.5[a]	14.5
1980	14.5	14.5
1985	14.5	34.0
2000	14.5	66.7
2020	70.6	84.5

[a] Acre-feet in thousands.

Economies of scale play a significant role in allocation. Depending on the degree of difference from the average unit cost, allocations can change significantly.

Wastewater treatment plants

Existing wastewater treatment facilities in subregion H need to be expanded by 1980 and probably replaced by 2020. The facilities in subregion F also need to be expanded by the year 2000, particularly with higher standards for effluent discharge (Tables 19a, b). However, according to the seasonal model, the expansion of facilities in both regions could be postponed a few more years. Only in region E is present wastewater treatment capacity sufficient until 2020.

To meet the required standard of effluent discharge in 1980, wastewater treatment plants capable of upgrading effluent to Level II are needed in all regions. In 1985, wastewater treatment plants to upgrade effluent to Level III are needed for effluents from region H and regions F and E. The treatment plant schedule also applies under seasonal variations, but the required capacities are different.

Table 19a. Required wastewater treatment plants capacity (100 ac-ft/year) (a) existing quality: annual vs. seasonal.

Region		1975	1980	1985	2000	2020
H	annual	6.8	9.8[a]	11.2[a]	15.7[a]	22.9[b]
	seasonal	4.4	6.2	7.2	10.0	14.6
F	annual	31.4	36.1	40.0	54.8[a]	77.0[a]
	seasonal	20.2	23.0	25.6	35.0	48.0[a]
E	annual	33.0	34.3	36.4	39.6	42.5
	seasonal	24.0	25.0	26.4	28.6	31.2

[a] Capacity expansion needed.

[b] New treatment plants will have to be built.

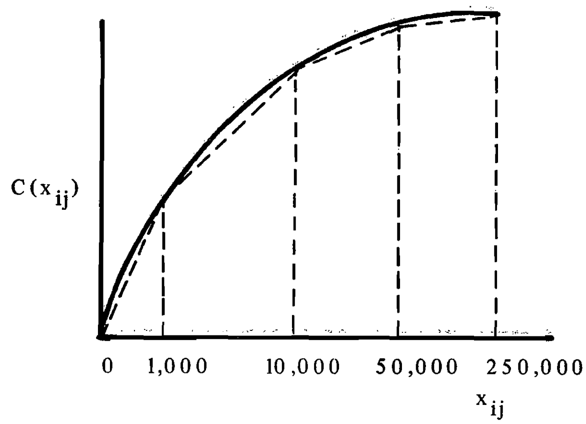
Table 19b. Required wastewater treatment plants capacity (100 ac-ft/year) (b) higher quality: annual vs. seasonal.

Year		H exis	H L2	H L3	F exis	F L2	F L3	E exis	E L2	E L3	Regional L1	Regional L2	Regional L3
1975	annual	6.8			31.4			33.0					
	seasonal	4.4			20.2			24.0					
1980	annual		9.8		36.1	36.1		34.3	34.3				
	seasonal		6.2		23.0	23.0		25.0	25.0				
1985	annual	8.4	11.2	0.8									76.4
	seasonal	7.2	7.2										62.0
2000	annual	8.4	15.7	5.7									94.4
	seasonal	8.4	10.0										73.6
2020	annual		22.9	12.9									119.5
	seasonal	8.4	10.0	6.2									80.2

Computer Time/Cost Comparisons

The model was solved using the Lambda formulation of the separable programming technique. A standard mathematical programming system (TEMPO), available with the Burrough's 6700, was used. Some of the important statistics of the program are discussed as follows.

In the separable formulation of the nonlinear cost function associated with the variable x_{ij}, the polygonal approximation of the functions are arrived at as follows. Assuming all x_{ij} to lie between 0 and 250,000 acre-feet, five grid points x_{ij}^k, k = 1, 2. . .5, were chosen in this range.



$$x_{ij}^1 = 0; x_{ij}^2 = 1{,}000; x_{ij}^3 = 10{,}000; x_{ij}^4 = 50{,}000;$$
$$x_{ij}^5 = 250{,}000$$

The decision variables are no longer x_{ij} s but they are the λ_{ij}^k. Once the λs are determine optimally, the x_{ij}^*, the optimal x_{ij} can be calculated with

$$x_{ij}^* = \sum_k \lambda_{ij}^k x_{ij}^k \qquad \text{for all i and j}$$

In order to avoid hand computation of the optimal x_{ij}, the above equation was defined as a free row in the problem. The restricted basis entry was implemented so that the λ variables entering the basis will always be adjacent.

In the seven-region model, there are 1010 variables in x_{ij} and five grid points which result in 5050 λ variables. There are 100 constraints of which 40 were in equalities and 60 were fixed rows. In addition, there were 1010 fixed rows corresponding to the constraints

$$\sum_k \lambda_{ij}^k = 1 \qquad \text{for all i and j}$$

Corresponding to 1010 variables of x_{ij}, 1010 constraints were defined as free rows. In addition, the objective function is a free row. Thus, there were 5050 variables and 2120 rows, or which 1110 were constraints. The cost of obtaining an optimal solution was as high as $450. Using an old basis, solutions to modified problems were obtained at an average cost of $90. The CPU time averaged 450 seconds for these runs and the memory requirement was about 17,500 kw/sec.

The three-region nonlinear model had 2079 variables and 644 rows, of which 356 were constraints. Solutions took about 100 sec. of CPU time and the memory requirement was about 2000 kw/sec. The cost of solutions obtained by starting from an old basis averaged about $20.

The linear solution cost is roughly about one tenth of the nonlinear solution, given similar starting conditions. Linear solutions were obtained using MPS/360 (IBM package) while the nonlinear solutions were obtained using TEMPO (Burrough's package).

REFERENCES

Aron, G., and V. H. Scott. 1971. Dynamic programming for conjunctive water use. ASCE, Journal of the Hydraulics Division 97(HY5):705.

Bayer, M. B. 1974. Nonlinear programming in river basin modeling. Water Resources Bulletin 10(2):311-317.

Berthouex, P. M. 1972. Evaluating economics of scale. Journal Water Pollution Control Federation 44:2111-2119.

Bishop, A. B., and D. W. Hendricks. 1971. Water reuse systems analysis. Water Resources Bulletin 7(3):542-553. June.

Bishop, A. B., W. J. Grenney, R. Narayanan, and S. L. Klemetson. 1974. Evaluating water reuse alternatives in water resource planning. Utah Water Research Laboratory, PRWG123-1, Utah State University, Logan, Utah.

Boehm, L. 1973. Should industry purchase or seek its own supply of water. Journal American Water Works Association 65:332.

Burroughs. 1973. Mathematical programming system user manual. TEMPO 6700. Burroughs Corp. Detroit, Michigan.

Butcher, W. S., Y. Y. Haimes, and W. A. Hall. 1969. Dynamic programming for the optimal sequencing of water supply projects. Water Resources Research 5(6):1196-1204.

Charnes, A., and W. W. Cooper. 1963. Deterministic Equivalents for optimizing and satisfying under chance constraints. Operations Research, Vol. 11, pp. 18-39.

Clyde, C. G., A. B. King, and J. C. Andersen. 1971. Application of operations research techniques for allocation of water resources in Utah. Utah Water Research Laboratory, PRWG 73-2. Utah State University, Logan, Utah.

Dawes, J. H. 1970. Tools for water resources study. Journal Irrigation and Drainage Division. American Society of Civil Engineers IR4:403.

DeVries, R. N., and C. G. Clyde. 1971. Optimization in municipal water supply system design. Water Resources Bulletin 7(5): 1048.

Eckenfelder, W. W., and C. E. Adams, Jr. 1972. Design and economics of joint wastewater treatment. Journal Sanitary Engineering Division, American Society of Civil Engineers 98:153.

Engineering News Record. 1974. Construction scoreboard. McGraw-Hill Publishers, weekly publication.

Engineering-Science. 1970. Deepwater interceptor feasibility study report. Prepared for Delaware River Basin Commission, Trenton, New Jersey.

Evenson, D. E., G T. Orlob, and J. R. Monser. 1969. Preliminary section of wastewater treatment systems. Journal of Water Pollution Control Federation 41:1845-1858.

Environmental Protection Agency and Sanitation Districts of Los Angeles County. 1971. Advanced waste treatment research facility-Pomona, California.

Federal Water Pollution Control Administration. 1967. Sewer and sewage treatment plant construction cost index. U.S. Government Printing Office, Washington, D.C.

Haimes, Y. Y., and W. S. Naiuis. 1974. Coordination of regional water resource supply and demand planning models. Water Resources Research. Forthcoming.

Haimes, Y. Y., M. A. Kaplan, and M. A. Husar. 1972. A multilevel approach to determining optimal taxation for the abatement of water pollution. Water Resources Research 8(2): 19-26.

Harl, E. N., R. A. Baldwin, and D. W. Hubly. 1971. An analysis of the economic implications of the permit system of water allocation. Iowa State Water Resources Research Institute, Ames, Iowa.

Hinomoto, H. 1972. Dynamic programming of capacity expansion of municipal water treatment system. Water Resources Research 8(5):1178-1187.

Hughes, T. C., and Calvin G. Clyde. 1973. Municipal water planning—mixed interger approach. Journal of the Hydraulics Division HY11:2079-2095. November.

Keith, John E., Jay C. Andersen, and Calvin G. Clyde. 1973. The economic efficiency of inter-basin agricultural water transfers in Utah: A mathematical programming approach. Utah Water Research Laboratory PRWG100-3. Utah State University, Logan, Utah.

Klemetson, S. L. 1974. Development of a dynamic programming model for the regionalization and staging of wastewater treatment plants. PhD. dissertation, Utah State University, Logan.

Koenig. L. 1967. The cost of water treatment by coagulation, sedimentation, and rapid sand filtration. Journal of the American Water Works Association 59:290.

Liebman, J. C., and H. M. David. 1968. Balas algorithm for zoned uniform treatment. Journal of Sanitary Engineering Division. American Society of Civil Engineers. 94(SA4):585-593.

Liebman, J. C., and W. R. Lynn. 1966. The optimal allocation of stream dissolved oxygen. Water Resources Research 2(3): 581-591.

Linaweaver, F. P., Jr., and C. S. Clark. 1964. Cost of water transmission cost. Journal American Water Works Association 56:1549.

Lofting, E. M., and P. H. McGauhey. 1968. Economic evaluation of water, Part IV: An input-output and linear programming analysis of California water requirements. Water Resources Center. University of California, Berkeley, California.

Loucks, D. P., C. S. Revelle, and W. R. Lynn. 1967. Linear programming models for water pollution control. Management Science 14(4):B166-188.

Lynn, W. R. 1964. Stage development of wastewater treatment works. Journal Water Pollution Control Federation 36(6): 722-751.

Lynn, W. R. 1966. Application of systems analysis to water and wastewater treatment. Journal of the American Water Works Association 58(6):651-656.

Lynn, W. R., J. A. Logan, and A. Charnes. 1962. Systems analysis for planning wastewater treatment plants. Journal Water Pollution Control Federation 34(6):565-581.

Milligan, J. H. 1969. Optimizing conjunctive use of groundwater and surface water. Utah Water Research Laboratory, PRWG42-4. Utah State University, Logan, Utah.

Morin, T. L. 1973. Optimal sequencing of capacity expansion projects. American Society of Civil Engineers. Journal Hydraulics Division 99(HY9):1605.

Mulvihill, E. M., and J. A. Dracup. 1974. Optimal timing and sizing of a conjunctive urban water supply and wastewater system with nonlinear programming. Water Resources Research 10(2):170-175.

Regev, Uri, and Aba Schwartz. 1973. Optimal path of interregional investment and allocation of water. Water Resources Research 9(2):251-262.

Smith, R. 1968. Cost of conventional and advanced treatment of wastewater. Journal Water Pollution Control Federation 40:1546.

Smith, R., and R. G. Eilers. 1970. Cost to the consumer of collecting and treating wastewater in the United States. U.S. Department of the Interior, Federal Water Quality Administration, Advanced Waste Treatment Branch, Division of Research, Cincinnati, Ohio.

U.S. Department of Commerce. 1974. Construction review. Cost and Prices 20(2):44.

U.S. Labor Statistics Bureau. 1974. Employment and earnings. Table C-2, Transportation and Public Utilities, SIC Code 494-7, Water, Steam, and Sanitary Systems (monthly publication).

Walker, W. R., and G. V. Skogerboe. 1973. The impact of water quality-objectives of urban water supply planning. Water Resources Bulletin 9(5):861.

Windsor, J. S., and V. T. Chow, 1972. Multireservoir optimization model. American Society of Civil Engineers 98(HY10): 1827-1845.

Young, G. K., and M. S. Pisano. 1970. Nonlinear programming applied to regional water resource planning. Water Resources Research 6(1):32-42.

APPENDICES

APPENDIX A

Treatment and Reuse Costs

ORIGIN 1: Surface water better than Class C

Destination A: Water treatment plants

The existing water treatment plants are located on mountain streams and draw no water from wells. The average cost of collecting water in nearby reservoirs and diverting it to water treatment plants was based on data for Salt Lake County. The cost of treating the water for culinary use was based on the existing treatment plants in Salt Lake City. The costs of distribution of the treated water to the consumer is not included.

(1) Water collection from river.

Since the entire system already existed the average total cost per acre-ft was applied to the approximate mean demand for water of 10,000 AF/YR, and a was set equal to 0.90 to develop the cost equation. The O & M costs were updated to 1974.

a) Capital
$4.12/AF @ 10,000 AF/YR
$y = 10.3\ x^{0.90}$

b) O & M
$9.23/AF (1973 prices)
$9.63/AF @ 10,000 AF/YR
$y = 24.1\ x^{0.90}$

c) Total
$13.35/AF (1973 prices, Bishop, et al., 1974, p. 34)
$13.75/AF @ 10,000 AF/YR
$y = 34.5\ x^{0.90}$ (Cost 1) *

(2) Water treatment - Existing plant

The average quantity of water treated by the existing treatment plants is 14,000 AF/YR. a for water treatment plants is 0.67 (Berthouex, 1972). Annual cost of capital was placed at 25 percent of total annual cost, and adjusted by one half the value indicated by the index since most of the costs were in operation in 1970.

a) Capital
$2.83/AF (1970 prices)
$3.47/AF @14,000 AF/YR
$y = 81.0\ x^{0.67}$

b) O & M
$8.47/AF (1970 prices)
$10.49/AF @ 14,000 AF/YR
$y = 245\ x^{0.67}$

*Key costs are designated by number in order to facilitate referencing particular costs used later in developing composite total cost figures.

c) Total
$11.30/AF (1970 prices, Bishop, et al., 1974, p.37)
$13.96/AF @ 14,000 AF/YR
$y = 326\, x^{0.67}$ (Cost 2)

(3) Composite cost equation *

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
1	Water collection	17.29	17,291	13.73	137,347	11.69	584,645
2	Water treatment	33.36	33,359	15.60	156,033	9.17	458,699
3	Total	50.65	50.650	29.33	293,380	20.86	1,043,344

Determine the slope of cost equation

$$a = \frac{LN\frac{Y_2}{Y_1}}{LN\frac{X_2}{X_1}} = \frac{LN\frac{1,043,344}{50,650}}{LN\frac{50,000}{1,000}} = 0.773$$

Determine cost coefficient, K, at 1,000 AF/YR

$$K = \frac{Y}{X^{0.773}} = \frac{50,650}{(1000)^{0.773}} = 243$$

$$y = K X^{a} = 243\, X^{0.773}$$ (Cost 3)

Destination B: Municipal culinary water

This alternative implies that a new plant would be built at current prices. Only small economies of scale are expected for the water distribution system because expansion is generally due to expansion of service area rather than service size.

(1) Water collection from river (See Cost 1)
(2) Water distribution

The distribution costs are based on annual reports for Salt Lake City. The average total cost per acre-ft was applied to the approximate mean demand for water of 10,000 AF/YR, and an economy of scale, a, of 0.90 was used to develop the cost equation. The O & M costs were updated.

a) Capital
$13.66/AF @ 10,000 AF/YR
$y = 34.3\, x^{0.90}$

b) O & M
$15.94/AF (1971 prices)
$18.59/AF @ 10,000 AF/YR
$y = 46.7\, x^{0.90}$

*Tables are shown for total costs only but the same method was also used for the capital and O & M cost equations.

c) Total
$29.60/AF (1971 prices, Bishop, et al., 1974, p. 34)
$32.25/AF @ 10,000 AF/YR
$y = 81.0 x^{0.90}$ (Cost 4)

(3) Water handling

Cost No.	Item	1000 AF/YR		10,000 AF/YR		50,000 AF/YR	
		$/AF	Total $	$/AF	Total $	$/AF	Total $
1	Water collection	17.29	17,291	13.73	137,347	11.69	584,645
4	Water distribution	40.60	40,596	32.25	322,467	27.45	1,372,644
5	Totals	57.89	57,887	45.98	459,814	39.14	1,957,890

$y = 115 x^{0.90}$ (Cost 5)

(4) Water treatment - New plant

The treatment plant cost is based on a 50 percent utilization of the plant capacity. Annual capital cost was placed at 25 percent of total annual cost.

a) Capital
$y = 131 x^{0.692}$ (1964 prices)
$y = 256 x^{0.692}$

b) O & M
$y = 430 x^{0.692}$ (1964 prices)
$y = 770 x^{0.692}$

c) Total
$y = 561 x^{0.692}$ (1964 prices, Koenig, 1967)
$y = 1026 x^{0.692}$ (Cost 6)

(5) Composite cost equation

Cost No.	Item	1000 AF/YR		10,000 AF/YR		50,000 AF/YR	
		$/AF	Total $	$/AF	Total $	$/AF	Total $
5	Water handling	57.89	57,887	45.98	459,814	39.14	1,957,890
6	Water treatment	122.22	122,221	60.14	601,378	36.63	1,831,617
7	Total	180.11	180,103	106.12	1,061,192	75.77	3,789,507

$y = 829 x^{0.779}$ (Cost 7)

Destination C: Industrial water

It was assumed that no treatment was necessary other than chlorination. The industries in Salt Lake County are located at varying distances from mountain streams so the reported cost for pumpage is considered to be approximate.

(1) Pumpage from river

The average economy of scale, a, for pumpage is 0.51 (Berthouex, 1972). Anual cost of capital was placed at 25 percent of total annual cost.

a) Capital
$1.96/AF (1971-72 prices)
$2.32/AF @ 19,363 AF/YR
$y = 292 x^{0.51}$

b) O & M
$5.86/AF (1971-72 prices)
$6.60/AF @ 19,363 AF/YR
$y = 832 x^{0.51}$

c) Total
$7.82/AF (1971-72 prices, Boehm, 1973)
$8.92/AF @ 19,363 AF/YR
$y = 1124 x^{0.51}$ (Cost 8)

(2) Chlorination

a) Annual capital cost
$y = 9.18 x^{0.658}$ (1967 prices, Smith, 1968, Figure 16)
$y = 16.3 x^{0.658}$

b) Annual O & M costs
$y = 6.05 x^{0.897}$ (1967 prices, Smith, 1968, Figure 16)
$y = 9.35 x^{0.897}$

c) Chlorination equation

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
	Annual Capital	1.54	1,535	0.70	6,985	0.40	20,142
	O& M	4.59	4,590	3.62	36,208	3.07	153,387
9	Total	6.13	6,125	4.32	43,193	3.47	173,529

$y = 16.7 x^{0.855}$ (Cost 9)

(3) Water handling

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
8	Water pumpage	38.09	38,086	12.32	123,244	5.60	280,054
9	Chlorination	6.13	6,125	4.32	43,193	3.47	173,529
10	Total	44.22	44,211	16.64	166,437	9.07	453,583

$y = 725 x^{0.595}$ (Cost 10)

(4) Composite cost equation (See Cost 10)
$y = 725 x^{0.595}$ (Cost 11)

Destination D: Agricultural water

(1) Diversion structures

Large economies of scale are possible with diversion structures, but since the actual cost is very dependent upon the terrain, an average value of $a = 0.90$ has been used. Annual cost of capital was placed at 75 percent of total annual cost.

a) Capital
$0.53/AF (1973 prices)
$0.57/AF @ 1960 AF/YR
$y = 1.18\,x^{0.90}$

b) O & M
$0.18/AF (1973 prices)
$0.19/AF @ 1,460 AF/YR
$y = 0.39\,x^{0.90}$

c) Total
$0.71/AF (1973 prices, Bishop et al., 1974, p. 36)
$0.76/AF @ 1,460 AF/YR
$y = 1.57\,x^{0.90}$ (Cost 12)

(2) Canal costs

Assuming that a canal is used by several farms, or industries, the cost equation represents the total cost of building and operating one mile of canal. The annual cost of capital was placed at 75 percent of the total annual cost. An economy of scale, *a*, of 0.26 was used (Linaweaver and Clark, 1964, Table 7). Since most of the canal system is already in existence, the cost of capital was increased only one half of that indicated by the cost index.

a) Capital
$2.39/AF/mi (1962 prices, Bishop et al., 1974, p. 36)
$2.47/AF/mi @ 22,393 AF/YR
$y = 4{,}091\,x^{0.26}$

b) O & M
$0.80/AF/mi (1962 prices)
$1.50/AF/mi @ 22,393 AF/YR
$y = 2{,}484\,x^{0.26}$

c) Total
$3.19/AF/mi (1962 prices)
$3.97/AF/mi @ 22,393 AF/YR
$y = 6{,}575\,x^{0.26}$ (Cost 13)

(3) Water handling

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
12	Diversion	0.79	787	0.63	6,250	0.53	26,605
13	Canal	39.62	39,618	7.21	72,093	2.19	109,554
14	Total	40.41	40,405	7.84	78,343	2.72	136,159

$y = 4{,}747\,x^{0.31}$ (Cost 14)

(4) Composite cost equation (See Cost 14)
$y = 4{,}747\,x^{0.31}$ (Cost 15)

ORIGIN 2: Water treatment plant

Destination B: Municipal culinary water

Since the water treatment plant is providing culinary water, only the cost of distributing the water is incurred

(1) Water distribution (See Cost 4)
(2) Composite cost equation (See Cost 4)
$y = 81.0 x^{0.90}$ (Cost 16)

Destination C: Industrial water

It was assumed that the industries using this supply will incur the same cost as municipal culinary water.

(1) Water distribution (See Cost 4)
(2) Composite cost equation (See Cost 4)
$y = 81.0 x^{0.90}$ (Cost 17)

Destination D: Agricultural water

It was assumed that the farms or private citizens using this supply will incur the same costs as municipal culinary water.

(1) Water distribution (See Cost 4)
(2) Composite cost equation (See Cost 4)
$y = 81.0 x^{0.90}$ (Cost 18)

ORIGIN 3: Wells

Destination A: Water treatment plants

The cost equation includes the cost of producing the well water and treating it in the existing water treatment plants.

(1) Well water

Most of the wells needed during the planning horizon are existing in a light use or capped state. The costs are based on Salt Lake County data.

a) Average well and pump characteristics (Bishop et al., 1974, p. 37)
   1) Casing size - 18"
   2) Casing depth - 805 ft
   3) Pump capacity - 1600 gpm, 2580 AF/YR
   4) Total lift - 507 ft
   5) Water pumped - 367 AF/YR/Pump
   6) 12 wells
   7) Total annual pumpage - 4,402 AF/YR
   8) Power cost - $13.92/AF
b) Capital costs for well casings and pumps

The pumps in Salt Lake County are operated at about 14 percent of capacity. Generally, there is a low limit to the production from an individual well, and therefore several wells are usually necessary to meet required water quantity demands. This would result in a low economy of scale, however, since these pumps are operated at a low level currently, the normal economy of scale for pumps of about 0.453 was used (Dawes, 1970, Figure 9).

   1) Annual costs (Bishop et al., 1974, p. 38)
      Well casings - $15,400 (Existing)
      Pumps - 20,100 (1973 prices)
      Pumps - 21,184
      Total - $36,584 @ 4,402 AF/YR
   2) $y = 818 x^{0.453}$

c) O & M costs

1) Annual costs (Bishop et al., 1974, p. 38)
Power costs \$13.92/AF @ 4,402 AF/YR
Pump & casing \$1,829/YR (0.05 of capital cost)
Total \$63,105 @ 4,402 AF/YR

2) $y = 33.2\ x^{0.90}$

d) Total
$y = 199\ x^{0.75}$ (Cost 19)

(2) Composite cost equation

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
19	Well water	35.39	35,388	19.90	199,000	13.31	665,397
2	Water treatment	33.36	33,359	15.60	156,033	9.17	458,699
20	Total	68.75	68,747	35.50	355,033	22,48	1,124,096

$y = 496\ x^{0.714}$ (Cost 20)

Destination B: Municipal culinary water

The cost equation includes the cost of producing the well water, chlorinating it, and distributing it to the consumer.

(1) Water handling

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
19	Well water	35.39	35,388	19.90	199,000	13.31	655,397
9	Chlorination	6.13	6,125	4.32	43,193	3.47	173,529
4	Distribution	40.60	40,596	32.25	322,467	27.45	1,372,644
21	Total	82.12	82,109	56.47	564,660	44.23	2,211,570

$y = 245\ x^{0.842}$ (Cost 21)

(2) Composite cost equation (See Cost 21)
$y = 245\ x^{0.842}$ (Cost 22)

Destination C: Industrial water

The cost equation includes the cost of producing the well water and chlorinating it. It was assumed that the well pump produces sufficient pressure for direct use by the industry.

(1) Water handling

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
19	Well water	35.39	35,388	19.90	199,000	13.33	665,397
9	Chlorination	6.13	6,125	4.32	43,193	3.47	173,529
23	Total	41.52	41,513	24.22	242,193	16.80	838,926

$y = 206\ x^{0.768}$ (Cost 23)

(2) Composite cost equation (See Cost 23)
$y = 206\ x^{0.768}$ (Cost 24)

Destination D: Agricultural water

It was assumed that the wells are located on the farms, and are used directly.

(1) Well water (See Cost 19)
(2) Composite cost equation (See Cost 19)
$y = 199\ x^{0.75}$ (Cost 25)

ORIGIN 4: Municipal effluent

Destination E: Existing secondary treatment plants

The cost equation includes the costs of collecting the wastewater from the sources and treating it in the existing secondary treatment plants.

(1) Sewage collection

The cost of sewage collection is based on the Salt Lake City data using the national averages of cost for 1968. Since most of the system already exists, the values were not adjusted to higher current costs.

a) National sewer collection data (Smith & Eilers, 1970)
1) Capital

House connection	$ 1.38
Municipal sewers	8.64
Interceptors and outfalls	2.46
	$12.48/Capita/YR

2) O & M

Municipal sewer maintenance	$ 0.86
Customer Service and Accounting	0.36
General and Administration	0.69
	$ 1.91/Capita/YR

b) Economy of scale (Smith & Eilers, 1970, Table III)
$a = 0.91$

c) Data for Salt Lake City (Bishop et al., 1974, p. 39)
Wastewater flow = 33.4 mgd = 37,300 AF/YR
Population (1970) = 174,870

d) Capital @ 37,300 AF/YR
$12.48/Capita/YR x 174,870 = $2,182,378
$y = 151\ x^{0.91}$

e) O & M @ 37,300 AF/YR
$1.91/Capita/YR x 174,870 = $334,002
$y = 23\ x^{0.91}$

f) Total @ 37,300 AF/YR
$14.39/Capita/YR x 174,870 = $2,516,379
$y = 174\ x^{0.91}$ (Cost 26)

(2) Existing secondary treatment plant

These plants exist, therefore, the reported capital costs for 1967 were used and the O & M costs were updated to 1974.

a) Capital - Trickling filter plants
$y = 137\ x^{0.784}$ (1967 prices, Smith, 1968, Figure 7)

b) O & M

$y = 201\ x^{0.668}$ (1967 prices, Smith, 1968, Figure 7)

$y = 311\ x^{0.668}$ (1974 prices)

c) Total

$y = 396\ x^{0.732}$ (Cost 27)

(3) Composite cost equation

Cost No.	Item	1000 AF/YR		10,000 AF/YR		50,000 AF/YR	
		$/AF	Total $	$/AF	Total $	$/AF	Total $
26	Sewage collection	93.44	93,444	75.95	759,537	65.71	3,285,579
27	Exist. Sec. Treat.	62.20	62,199	33.35	333,516	21.80	1,090,004
28	Total	155.64	155,643	109.30	1,093,053	87.51	4,375,583

$y = 430\ x^{0.853}$ (Cost 28)

Destination F: Wastewater treatment plant - Level 1

The cost equation includes the costs of collecting the wastewater from the source and treating it at a new secondary treatment plant with activated sludge.

(1) Sewage collection (See Cost 26)

(2) New wastewater treatment plant - Level 1

a) Capital - Activated sludge plants

$y = 138\ x^{0.780}$ (1967 prices, Smith, 1968, Figure 6)

$y = 253\ x^{0.780}$

b) O & M

$y = 155\ x^{0.756}$ (1967 prices, Smith, 1968, Figure 6)

$y = 240\ x^{0.756}$

c) Total

$y = 489\ x^{0.770}$ (Cost 29)

(3) Composite cost equation

Cost No.	Item	1000 AF/YR		10,000 AF/YR		50,000 AF/YR	
		$/AF	Total $	$/AF	Total $	$/AF	Total $
26	Sewage Collection	93.44	93,444	75.95	759,537	65.71	3,285,579
29	New WTP-Level 1	99.83	99,834	58.71	587,154	40.54	2,026,666
30	Total	193.27	193,278	134.66	1,346,691	106.25	5,312,245

$y = 556\ x^{0.847}$ (Cost 30)

Destination G: Wastewater treatment plant - Level 2

The cost equation includes the costs of collecting the wastewater from the source and treating it in a new tertiary treatment plant with activated sludge followed by rapid sand filtration.

(1) Sewage collection (See Cost 26)

(2) Rapid sand filtration

a) Capital
$y = 51.8\,x^{0.662}$ (1967 prices, Smith, 1968, Figure 9)
$y = 95.0\,x^{0.662}$

b) O & M
$y = 252\,x^{0.638}$ (1967 prices, Smith, 1968, Figure 9)
$y = 390\,x^{0.638}$

c) Total
$y = 481\,x^{0.644}$ (Cost 31)

(3) New wastewater treatment plant - Level 2

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
29	New WTP-Level 1	99.83	99,834	58.71	587,154	40.54	2,026,666
31	Rapid sand filter	41.13	41,129	18.12	181,195	10.22	510,836
32	Total	140.96	140,963	76.83	768,349	50.76	2,537,502

$y = 855\,x^{0.739}$ (Cost 32)

(4) Composite cost equation

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
26	Sewage collection	93.44	93,444	75.95	759,537	65.71	3,285,579
32	New WTP-Level 2	140.96	140,963	76.83	768,349	50.76	2,537,502
33	Total	234.40	234,407	152.78	1,527,886	116.47	5,823,081

$y = 807\,x^{0.821}$ (Cost 33)

Destination H: Wastewater treatment plant - Level 3

The cost equation includes the costs of collecting the wastewater from the source and treating it in a new tertiary treatment plant with activated sludge followed by rapid sand filtration and carbon adsorption.

(1) Sewage collection (See Cost 26)

(2) Carbon adsorption

a) Capital
$y = 281\,x^{0.626}$ (1967 prices, Smith, 1968, Figure 11)
$y = 515\,x^{0.626}$

b) O & M
$y = 226\,x^{0.724}$ (1967 prices, Smith, 1968, Figure 11)
$y = 349\,x^{0.724}$

c) Total
$y = 794\,x^{0.686}$ (Cost 34)

(3) New wastewater treatment plant - Level 3

Cost No.	Item	1000 AF/YR		10,000 AF/YR		50,000 AF/YR	
		$/AF	Total $	$/AF	Total $	$/AF	Total $
29	New WTP-Level 1	99.83	99,834	58.71	587,154	40.54	2,026,666
31	Rapid sand filter	41.13	41,129	18.12	181,195	10.22	510,836
34	Carbon adsorption	90.74	90,745	44.04	440,373	26.57	1,328,354
35	Total	231.70	231,708	120.87	1,208,722	77.33	3,865,856

$y = 1{,}603\ x^{0.720}$ (Cost 35)

(4) Composite cost equation

Cost No.	Item	1000 AF/YR		10,000 AF/YR		50,000 AF/YR	
		$/AF	Total $	$/AF	Total $	$/AF	Total $
26	Sewage collection	93.44	93,444	75.95	759,537	65.71	3,285,579
35	New WTP-Level 3	231.70	231,708	120.87	1,208,722	77.33	3,865,856
36	Total	325.14	325,152	196.82	1,968,259	143.04	7,151,435

$y = 1{,}387\ x^{0.79}$ (Cost 36)

Destination I: Wastewater treatment plant - Reuse

The cost equation includes the costs of collecting the wastewater from the source and treating it in a new tertiary treatment plant to a quality suitable for direct use as culinary water. The plant consists of an activated sludge process followed by rapid sand filtration, carbon adsorption, and ion exchange.

(1) Sewage collection (See Cost 26)
(2) Ion exchange

One third of the flow of the plant is processed through the ion exchange unit and then blended with the remaining flow.

a) Capital
$y = 86\ x^{0.841}$ (1970 prices, EPA, 1971)
$y = 128\ x^{0.841}$
$y = 42.7\ x^{0.841}$ (33% blend)

b) O & M
$y = 531\ x^{0.841}$ (1970 prices, EPA, 1971)
$y = 658\ x^{0.841}$
$y = 219\ x^{0.841}$ (33% blend)

c) Total
$y = 617\ x^{0.841}$ (1970 prices, EPA, 1971)
$y = 786\ x^{0.841}$
$y = 262\ x^{0.841}$ (Cost 37)

(3) New wastewater treatment plant - Reuse

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
29	New WTP-Level 1	99.83	99,834	58.71	587,154	40.54	2,026,666
31	Rapid sand filter	41.13	41,129	18.12	181,195	10.22	510,836
34	Carbon adsorption	90.74	90,745	44.04	440,373	26.57	1,328,354
37	Ion exchange	87.36	87,358	60.58	605,761	46.90	2,344,958
38	Total	319.06	319,066	181.45	1,814,483	124.23	6,210,814

$y = 1{,}686\ x^{0.759}$ (Cost 38)

(4) Composite cost equation

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
26	Sewage collection	93.44	93,444	75.95	759,537	65.71	3,285,579
38	New WTP-Reuse	319.06	319,066	181.45	1,814,483	124.23	6,210,814
39	Total	412.50	412,510	257.40	2,574,020	189.94	9,496,393

$y = 1{,}620\ x^{0.802}$ (Cost 39)

ORIGIN 5: Industrial effluents

Destination E: Existing secondary wastewater treatment plants

The cost equation includes the costs of collecting the wastewaters from the source, pretreating it, and then treating it in an existing trickling filter plant.

(1) Sewage collection (See Cost 26)
(2) Pretreatment (Eckenfelder and Adams, 1972)
  a) Capital
    $y = 13.7\ x^{0.63}$ (1969 prices)
    $y = 21.2\ x^{0.63}$
  b) O & M
    $y = 21.8\ x^{0.684}$ (1969 prices)
    $y = 29.3\ x^{0.684}$
  c) Total
    $y = 49.4\ x^{0.667}$ (Cost 40)
(3) Sewage handling

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
26	Sewage collection	93.44	93,444	75.95	759,537	65.71	3,285,579
40	Pretreatment	4.95	4,951	2.30	23,000	1.35	67,288
41	Total	98.39	98,395	78.25	782,537	67.06	3,352,867

$y = 194\ x^{0.902}$ (Cost 41)

(4) Composite cost equation

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
41	Sewage handling	98.39	98,395	78.25	782,537	67.06	3,352,867
27	Exist. Sec. Treat.	62.20	62,199	33.35	333,516	21.80	1,090,004
42	Total	160.59	160,594	111.60	1,116,053	88.86	4,442,871

$y = 459 x^{0.848}$ (Cost 42)

Destination F: Wastewater treatment plant - Level 1

The cost equation includes the costs of collecting the wastewater from the source, pretreating it, and then treating it in a new activated sludge plant.

(1) Sewage handling (See Cost 41)
(2) New wastewater treatment plant - Level 1 (See Cost 29)
(3) Composite cost equation

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
41	Sewage handling	98.39	98,395	78.25	782,537	67.06	3,352,867
29	New WTP-Level 1	99.83	99,834	58.71	587,154	40.54	2,026,666
43	Total	198.22	198,229	136.96	1,369,691	107.60	5,379,533

$y = 583 x^{0.844}$ (Cost 43)

Destination G: Wastewater treatment plant - Level 2

The cost equation includes the costs of collecting the wastewater from the source, pretreating it, and then treating it in a new activated sludge plant with a rapid sand filter for tertiary treatment.

(1) Sewage handling (See Cost 41)
(2) New wastewater treatment plant - Level 2 (See Cost 32)
(3) Composite cost equation

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
41	Sewage handling	98.39	98,395	78.25	782,537	67.06	3,352,867
32	New WTP-Level 2	140.96	140,963	76.83	768,349	50.76	2,537,502
44	Total	239.35	239,358	155.08	1,550,886	117.82	5,890,369

$y = 836 x^{0.819}$ (Cost 44)

Destination H: Wastewater treatment plant - Reuse

The cost equation includes the costs of collecting the wastewater from the source, pretreating it, and then treating it in a new activated sludge plant with a rapid sand filter and carbon adsorption for tertiary treatment.

(1) Sewage handling (See Cost 41)
(2) New wastewater treatment plant - Level 3 (See Cost 35)
(3) Composite cost equation

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
41	Sewage handling	98.39	98,395	78.25	782,537	67.06	3,352,867
35	New WTP-Level 3	231.70	231,708	120.87	1,208,722	77.33	3,865,856
45	Total	330.09	330,103	199.12	1,991,259	144.39	7,218,723

$y = 1{,}419\ x^{0.789}$ (Cost 45)

Destination I: Wastewater treatment plant - Reuse

The cost equation includes the costs of collecting the wastewater from the source, pretreating it, and treating it to a quality for use as culinary water. The plant consists of activated sludge followed by rapid sand filters, carbon adsorption, and ion exchange for tertiary treatment. One third of the water is processed through the ion exchange unit and reblended with the main stream.

(1) Sewage handling (See Cost 41)
(2) New wastewater treatment plant - Reuse (See Cost 38)
(3) Composite cost equation

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
41	Sewage handling	98.39	98,395	78.25	782,537	67.06	3,352,867
38	New WTP-Reuse	319.06	319,066	181.45	1,814,483	124.23	6,210,814
46	Total	417.45	417,461	259.70	2,597,020	191.29	9,563,681

$y = 1{,}662\ x^{0.800}$ (Cost 46)

ORIGIN 6: Existing secondary wastewater treatment plants

Destination D: Agricultural water

The cost equation includes the costs of transporting treated effluent in canals and distribution of water at diversion structures.

(1) Water handling (See Cost 14)
(2) Composite cost equation (See Cost 14)
$y = 4{,}747\ x^{0.31}$ (Cost 47)

Destination G: Water treatment plant - Level 2

The cost equation includes the costs of adding a rapid sand filter as a tertiary process to an existing plant. There are no additional water handling costs.

(1) Tertiary - Level 1-2 (See Cost 31)
$y = 481\ x^{0.644}$ (Cost 48)
(2) Composite cost equation (See Cost 48)
$y = 481\ x^{0.644}$ (Cost 49)

Destination H: Wastewater treatment plant - Level 3

The cost equation includes the costs of adding a rapid sand filter and carbon adsorption units as tertiary processes to an existing plant. There are no additional water handling costs.

(1) Tertiary - Level 1-3

Cost No.	Item	1000 AF/YR		10,000 AF/YR		50,000 AF/YR	
		$/AF	Total $	$/AF	Total $	$/AF	Total $
31	Rapid sand filter	41.13	41,129	18.12	181,195	10.22	510,836
34	Carbon adsorption	90.74	90,745	44.04	440,373	26.57	1,328,354
50	Total	131.87	131,874	62.16	621,568	36.79	1,839,190

$y = 1{,}254\ x^{0.674}$ (Cost 50)
(2) Composite cost equation (See Cost 50)
$y = 1{,}254\ x^{0.674}$ (Cost 51)

Destination I: Wastewater treatment plant - Reuse

The cost equation includes the costs of adding tertiary treatment processes to an existing treatment plant to produce water suitable for culinary water. The tertiary plant consists of a rapid sand filter, carbon adsorption, and an ion exchange unit treating one third of the total flow. The flows are reblended. There are no additional water handling costs.

(1) Tertiary - Level 1-R

Cost No.	Item	1000 AF/YR		10,000 AF/YR		50,000 AF/YR	
		$/AF	Total $	$/AF	Total $	$/AF	Total $
31	Rapid sand filter	41.13	41,129	18.12	181,195	10.22	510,836
34	Carbon adsorption	90.74	90,745	44.04	440,373	26.57	1,328,354
37	Ion exchange	87.36	87,358	60.58	605,761	46.90	2,344,958
52	Total	219.23	219,232	122.74	1,227,329	83.69	4,184,148

$y = 1{,}199\ x^{0.754}$ (Cost 52)
(2) Composite cost equation (See Cost 52)
$y = 1{,}199\ x^{0.754}$ (Cost 53)

ORIGIN 7: Wastewater treatment - Level 1

Destination D: Agricultural water

The cost equation includes the costs of transporting the treated effluent from a new activated plant and distributing the water at diversion structures.

(1)	Water handling	(See Cost 14)
(2)	Composite cost equation	(See Cost 14)
	$y = 4{,}747\ x^{0.31}$	(Cost 54)

Destination G: Wastewater treatment - Level 2

The cost equation includes the costs of adding a rapid sand filter as a tertiary treatment process to a new activated sludge treatment plant. The costs were increased 5 percent to force the use of the existing secondary treatment plants over the construction of new ones. There are no additional water handling costs.

(1)	Tertiary - Level N-2	
	$y = 481\ x^{0.644}$	(See Cost 31)
	$y = 505\ x^{0.644}$	(Cost 55)
(2)	Composite cost equation	(See Cost 55)
	$y = 505\ x^{0.644}$	(Cost 56)

Destination H: Wastewater treatment plant - Level 3

The cost equation includes the costs of adding a rapid sand filter and carbon adsorption units as tertiary processes to a new activated sludge plant. The costs were increased 5 percent to force the use of the existing secondary treatment plants over the construction of new ones. There are no additional water handling costs.

(1)	Carbon adsorption	
	$y = 794\ x^{0.686}$	(See Cost 34)
	$y = 834\ x^{0.686}$	(Cost 57)
(2)	Tertiary - Level N-3	
	$y = 1{,}254\ x^{0.674}$	(See Cost 50)
	$y = 1{,}317\ x^{0.674}$	(Cost 58)
(3)	Composite cost equation	(See Cost 58)
	$y = 1{,}317\ x^{0.674}$	(Cost 59)

Destination I: Wastewater treatment plant - Reuse

The cost equation includes the costs of adding tertiary treatment processes to a new activated sludge plant to produce water suitable for culinary use. The tertiary treatment consists of rapid sand filter, carbon adsorption, and ion exchange units. The ion exchange units process one third of the total water flow and then blend with main stream. The costs were increased 5 percent to force the use of the existing treatment plants over the construction of new ones. There are no additional water handling costs.

(1)	Ion exchange (33% blend)	
	$y = 262\ x^{0.841}$	(See Cost 37)
	$y = 275\ x^{0.841}$	(Cost 60)
(2)	Tertiary - Level N-R	
	$y = 1{,}199\ x^{0.754}$	(See Cost 52)
	$y = 1{,}259\ x^{0.754}$	(Cost 61)
(3)	Composite cost equation	(See Cost 61)
	$y = 1{,}259\ x^{0.754}$	(Cost 62)

ORIGIN 8: Wastewater treatment plant - Level 2

Destination C: Industrial water

Treatment level 2 produces a water of a quality suitable for direct reuse by industry. The cost equation contains only the approximate cost of pumping the water.

(1)	Pumping	(See Cost 8)
(2)	Composite cost equation	(See Cost 8)
	$y = 1{,}124\ x^{0.51}$	(Cost 63)

Destination D: Agricultural water

The cost equation includes the costs of transporting treated effluent in canals and distributing it at diversion structures.

(1)	Water handling	(See Cost 14)
(2)	Composite cost equation	(See Cost 14)
	$y = 4{,}747\ x^{0.31}$	(Cost 64)

Destination H: Wastewater treatment plant - Level 3

The cost equation includes the costs of adding a carbon adsorption unit to new level 2 treatment plant. The costs were increased 5 percent to force the use of existing treatment plants over the construction of new plants. There are no additional water handling costs.

(1)	Tertiary - Level 2-3	
	$y = 794\ x^{0.686}$	(See Cost 34)
	$y = 834\ x^{0.686}$	(See Cost 57)
(2)	Composite cost equation	(See Cost 57)
	$y = 834\ x^{0.686}$	(Cost 65)

Destination I: Wastewater treatment plant - Reuse

The cost equation includes the costs of adding carbon adsorption and ion exchange units to produce water suitable for culinary use. The costs were increased 5 percent to force the use of existing treatment plants over the construction of new plants. There are no additional water handling costs.

(1)	Carbon adsorption	
	$y = 794\ x^{0.686}$	(See Cost 34)
	$y = 834\ x^{0.686}$	(See Cost 57)
(2)	Ion exchange (33% blend)	
	$y = 262\ x^{0.841}$	(See Cost 37)
	$y = 275\ x^{0.841}$	(See Cost 60)
(3)	Tertiary - Level 2-R	

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
34	Carbon adsorption	90.74	90,745	44.04	440,373	26.57	1,328,354
37	Ion exchange	87.36	87,358	60.58	605,761	46.90	2,344,958
-	Total	178.10	178,103	104.62	1,046,134	73.47	3,673,312

	$y = 849\ x^{0.774}$	
	$y = 891\ x^{0.774}$	(Cost 66)
(4)	Composite cost equation	(See Cost 66)
	$y = 891\ x^{0.774}$	(Cost 67)

ORIGIN 9: Wastewater treatment plant - Level 3

Destination A: Water treatment plants

The cost equation includes the costs of a pipeline and pump for the transmission of treated effluent to the water treatment plants.

(1) Constraints
  a) Pipe line length - 8 miles
  b) Pump lift - 1000 feet
  c) Pump efficiency - 0.092
  d) Power cost - $0.02/kw-hr

(2) Pipelines (1970 prices, Bishop et al., 1974, p. 44)

The cost equation for the pipeline includes the annual capital and O & M costs, and also the cost of pumping necessary to overcome headloss. It does not include the cost of pumping to change elevation. The equation is based on the following values:

Slope = 2 ft/1000 ft, down hill
Power = $0.02/kw-hr
Efficiency = 0.92
C = 120

It was assumed that capital repayment accounted for 75 percent of the total annual payment.

a) Capital
  $y = 134\ x^{0.535}$ $/mi (1970 prices)
  $y = 193\ x^{0.535}$ $/mi
  $y = 1{,}544\ x^{0.535}$ $/8 mi
b) O & M
  $y = 45.0\ x^{0.535}$ $/mi (1970 prices)
  $y = 56.0\ x^{0.535}$ $/mi
  $y = 448\ x^{0.535}$ $/8 mi
c) Total
  $y = 179\ x^{0.535}$ $/mi (1970 prices)
  $y = 249\ x^{0.535}$ $/mi
  $y = 1{,}992\ x^{0.535}$ $/8 mi (Cost 68)

(3) Pumping (Dawes, 1970, Figure 12)

It was assumed that the pumps included with the pipeline are adequate to pump to the required heads. Therefore, only the cost of power required to pump the required heads are included in this section. An economy of scale of 0.90 was used to account for power rate charts.

a) O & M

$$y = \frac{3.148\ H\ x^{0.90}\ P}{Eo}$$

  where y = dollars
    H = feet of pump lift
    x = AF/YR
    P = Price of power, $0.02/kw-hr
    Eo = Pump efficiency, 0.92

  $y = 0.0684\ H\ x^{0.90}$
  for H = 1000 ft
  $y = 68.4\ x^{0.90}$
b) Total
  $y = 68.4\ x^{0.90}$ (Cost 69)

(4) Water transmission

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
68	Pipeline	80.22	80,221	27.50	274,973	13.01	650,486
69	Pumping	34.28	34,281	27.23	272,305	23.18	1,159,122
70	Total	114.50	114,502	54.73	547,278	36.19	1,809,608

$y = 873\ x^{0.706}$ (Cost 70)
(5) Composite cost equation (See Cost 70)
$y = 873\ x^{0.706}$ (Cost 71)

Destination C: Industrial water

The cost equation includes only the costs of pumpage of treated effluent to the local industries.

(1) Pumpage (See Cost 8)
(2) Composite cost equation (See Cost 8)
$y = 1{,}124\ x^{0.51}$ (Cost 72)

Destination D: Agricultural water

The cost equation includes the costs of transporting the treated effluent in canals and distributing it at diversion structures.

(1) Water handling (See Cost 14)
(2) Composite cost equation (See Cost 14)
$y = 4{,}747\ x^{0.31}$ (Cost 73)

Destination I: Wastewater treatment plant - Reuse

The cost equation includes the costs of adding an ion exchange unit to a new level 2 treatment plant to produce water of quality suitable for use as culinary water. There are no additional water handling costs. Costs are increased 5 percent to force the use of existing plants rather than the construction of new plants.

(1) Ion exchange (33% blend)
$y = 262\ x^{0.841}$ (See Cost 37)
$y = 275\ x^{0.841}$ (See Cost 60)
(2) Tertiary - Level 3-R (See Cost 60)
$y = 275\ x^{0.841}$ (Cost 74)
(3) Composite cost equation (See Cost 74)
$y = 275\ x^{0.841}$ (Cost 75)

ORIGIN 10: Wastewater treatment plant - Reuse

Destination B: Municipal culinary water

The water produced by this treatment plant is suitable for direct reuse as culinary water, and can be connected directly to the water distribution system. The cost equation contains only the distribution costs. The treatment sequence used in this economic analysis is representative of the costs that will be incurred for water reuse as culinary water, but it does imply that this sequence is required or will be approved.

(1) Water distribution (See Cost 4)
(2) Composite cost equation (See Cost 4)
$y = 81.0\ x^{0.90}$ (Cost 76)

Destination C: Industrial water

The cost equation includes the costs of pumping the treated effluent to the industrial users. This option assumes that the industrial users will be supplied with a separate pipeline rather than obtaining water from the city water distribution system.

(1) Water pumpage (See Cost 8)
(2) Composite cost equation (See Cost 8)
$y = 1{,}124\ x^{0.51}$ (Cost 77)

Destination D: Agricultural water

The cost equation includes the costs of transporting the treated effluent in canals and distributing it at diversion structures.

(1) Water handling (See Cost 14)
(2) Composite cost equation (See Cost 14)
$y = 4{,}747\ x^{0.31}$ (Cost 78)

ORIGIN 11: Surface water worse than Class C

Destination A: Water treatment plant

The cost equation includes the costs of pretreating the river water to bring it to the level of quality existing in the rivers that are classed as being better than Class C. The costs of collecting the water from the river and treating it in an existing water treatment plant is also included.

(1) Water pretreatment

A cost equivalent to that required for a separate coagulation and sedimentation unit is necessary for pretreatment.

a) Capital
$y = 5.56\ x^{0.899}$ (1967 prices, Smith, 1968, Figure 8)
$y = 10.2\ x^{0.899}$
b) O & M
$y = 12.16\ x^{0.969}$ (1967 prices, Smith, 1968, Figure 8)
$y = 18.8\ x^{0.969}$
c) Total
$y = 28.0\ x^{0.953}$ (Cost 79)

(2) Water handling

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
79	Water pretreatment	20.24	20,238	18.16	181,618	16.84	841,931
1	Water collection	17.29	17,291	13.73	137,347	11.69	584,645
80	Total	37.53	37,529	31.89	318,965	28.53	1,426,576

$y = 60.9\ x^{0.930}$ (Cost 80)

(3) Composite cost equation

Cost No.	Item	1000 AF/YR		10,000 AF/YR		50,000 AF/YR	
		$/AF	Total $	$/AF	Total $	$/AF	Total $
80	Water handling	37.53	37,529	31.89	318,965	28.53	1,426,576
2	Water treatment	33.36	33,359	15.60	156,033	9.17	458,699
81	Total	70.89	70,888	47.49	474,998	37.70	1,885,275

$y = 216\ x^{0.839}$ (Cost 81)

Destination B: Municipal culinary water

The cost equation includes the costs of collecting the water from the river, pretreating it, treating it in a new water treatment plant, and then distributing it to the customers.

(1) Water handling

Cost No.	Item	1000 AF/YR		10,000 AF/YR		50,000 AF/YR	
		$/AF	Total $	$/AF	Total $	$/AF	Total $
1	Water collection	17.29	17,291	13.73	137,347	11.69	584,645
79	Water pretreatment	20.24	20,238	18.16	181,618	16.84	841,931
4	Water distribution	40.60	40,596	32.25	322,467	27.45	1,372,644

$y = 141\ x^{0.915}$ (Cost 82)

(2) Composite cost equation

Cost No.	Item	1000 AF/YR		10,000 AF/YR		50,000 AF/YR	
		$/AF	Total $	$/AF	Total $	$/AF	Total $
82	Water handling	78.13	78,125	64.14	641,432	55.98	2,799,220
6	Water treatment	122.22	122,221	60.14	601,378	36.63	1,831,617
83	Total	200.35	200,346	124.28	1,242,810	92.61	4,630,837

$y = 782\ x^{0.803}$ (Cost 83)

Destination C: Industrial water

It was assumed that a pretreatment by coagulation and sedimentation, followed by chlorination, provided sufficient treatment for use by industries. The industries in Salt Lake County are located at varying distances from mountain streams so the reported cost for pumpage is considered to be approximate.

(1) Water treatment

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
79	Water pretreatment	20.24	20,238	18.16	181,618	16.84	841,931
9	Chlorination	6.13	6,125	4.32	43,193	3.47	173,529
84	Total	26.37	26,363	22.48	224,811	20.31	1,015,460

$y = 41.9\ x^{0.933}$ (Cost 84)

(2) Water handling

Cost No.	Item	1000 AF/YR $/AF	1000 AF/YR Total $	10,000 AF/YR $/AF	10,000 AF/YR Total $	50,000 AF/YR $/AF	50,000 AF/YR Total $
8	Water pumpage	38.09	38,086	12.32	123,244	5.60	280,054
79	Water pretreatment	20.24	20,238	18.16	181,618	16.84	841,931
9	Chlorination	6.13	6,125	4.32	43,193	3.47	173,529
85	Total	64.46	64,449	34.80	348,055	25.91	1,295,514

$y = 322\ x^{0.767}$ (Cost 85)

(3) Composite cost equation (See Cost 85)

$y = 322\ x^{0.767}$ (Cost 86)

Destination D: Agricultural water

The cost equation includes the costs of transporting the treated effluent in canals and distributing it at diversion structures.

(1) Water handling (See Cost 14)

(2) Composite cost equation (See Cost 14)

$y = 4{,}747\ x^{0.31}$ (Cost 87)

ORIGIN 12: Central Utah Project - Jordan Narrows water treatment plant

Destination B: Municipal culinary water

The cost equation includes a fixed charge of 55 dollars per acre-foot for the water and a distribution cost.

(1) Purchase price

It was assumed that 50 percent of the price of the water was expended on capital repayment.

a) Capital

$y = 27.5\ x^{1.0}$

b) O & M

$y = 27.5\ x^{1.0}$

c) Total

$y = 55.0\ x^{1.0}$ (Cost 88)

(2) Water handling

Cost No.	Item	1000 AF/YR		10,000 AF/YR		50,000 AF/YR	
		$/AF	Total $	$/AF	Total $	$/AF	Total $
88	Purchase price	55.00	55,000	55.00	550,000	55.00	2,750,000
4	Distribution	40.60	40,596	32.35	322,467	27.45	1,372,644
89	Total	95.60	95,596	87.25	872,467	82.45	4,122,644

$y = 124\ x^{0.962}$ (Cost 89)

(3) Composite cost equation (See Cost 89)

$y = 124\ x^{0.962}$ (Cost 90)

Destination C: Industrial water

The cost equation includes a purchase price of the water that ranges from 62 to 110 dollars per acre-foot, and the cost of pumping the water to industry.

(1) Purchase price

It was assumed that 50 percent of the price of the water was expended on capital repayment. The price was distributed at $110/AF at one AF/YR and $62/AF at 50,000 AF/YR.

a) Capital

$y = 55\ x^{0.947}$

b) O & M

$y = 55\ x^{0.947}$

c) Total

$y = 110\ x^{0.947}$ (Cost 91)

(2) Water handling

Cost No.	Item	1000 AF/YR		10,000 AF/YR		50,000 AF/YR	
		$/AF	Total $	$/AF	Total $	$/AF	Total $
8	Water pumpage	38.09	38,086	12.32	123,244	5.60	280,054
91	Purchase price	76.28	76,276	67.51	675,138	62.00	3,099,683
92	Total	114.37	114,362	79.83	798,382	67.60	3,379,737

$y = 289\ x^{0.866}$ (Cost 92)

(3) Composite cost equation (See Cost 92)

$y = 289\ x^{0.866}$ (Cost 93)

Destination D: Agricultural water

The cost equation includes a purchase price of the water that ranges from 62 to 110 dollars per acre-foot, and the cost of pumping water to industry.

(1) Purchase Price (See Cost 91)

(2) Water handling (See Cost 92)

(3) Composite cost equation (See Cost 93)

$y = 289\ x^{0.866}$ (Cost 94)

Water Transmission Costs

A. Base cost (See Cost 68)

The cost equation for the pipeline includes the costs of the pipe, pump, and power required to overcome head loss. It does not include the cost of pumping to change elevation.

(1) Capital
$y = 193\ x^{0.535}\ L$
where y = Dollars
X = AF/YR
L = Length in miles
(2) O & M
$y = 56.0\ x^{0.535}\ L$
(3) Total
$y = 249\ x^{0.535}\ L$ (Cost 95)

B. Pumping costs (See Cost 69)

It was assumed that the pumps included with the pipeline are adequate to pump the water to the required head. Therefore only the cost of power was included in this section.

(1) Capital
$y = 0$
(2) O & M
$y = 0.0684\ x^{0.90}\ H$
where y = Dollars
X = AF/YR
H = Feet of pump lift
(3) Total
$y = 0.0684\ x^{0.90}\ H$ (Cost 96)

C. Total water transmission costs

(1) $y = 249\ x^{0.535}\ L + 0.0684\ x^{0.90}\ H$ (Cost 97)
where y = Dollars
X = AF/YR
L = Length in miles
H = Feet of pump lift

D. Elevations

Table A-1. Elevations of origins and destination.

District \ Source or Dist.	Wells	Municipal	Industrial	Agricultural	SW>C[a]	SW<C	Wastewater Treatment Plant	Water Treatment Plant	Central Utah Project
H_2	4340	4340	4340	4390	-	4290	4300	-	-
H_1	4600	4500	5000	4425	-	4290	-	-	-
G	4365	4270	4270	5200	5200	4255	4265	5000	4275
F_2	4350	4350	4260	4800	5000	4230	4260	5600	-
F_1	4280	4280	4255	4350	-	4230	4240	-	4270
E	4265	4265	4265	5000	5000	4220	4240	6000	-
D	4240	4265	4230	4235	-	-	4240	-	-

[a]SW > C - Surface water quality better than Class C.

E. Transportation distances

The central of each source of water was determined for each district. The straight line path distance in miles was determined between each possible origin and destination. Where path must run the canyons, this path was used. A map of the origins and destinations is shown in Figure A-1 and the distance matrix is shown in Figure A-2. Water classified as worse that Class C was taken from the nearest location on the Jordan River.

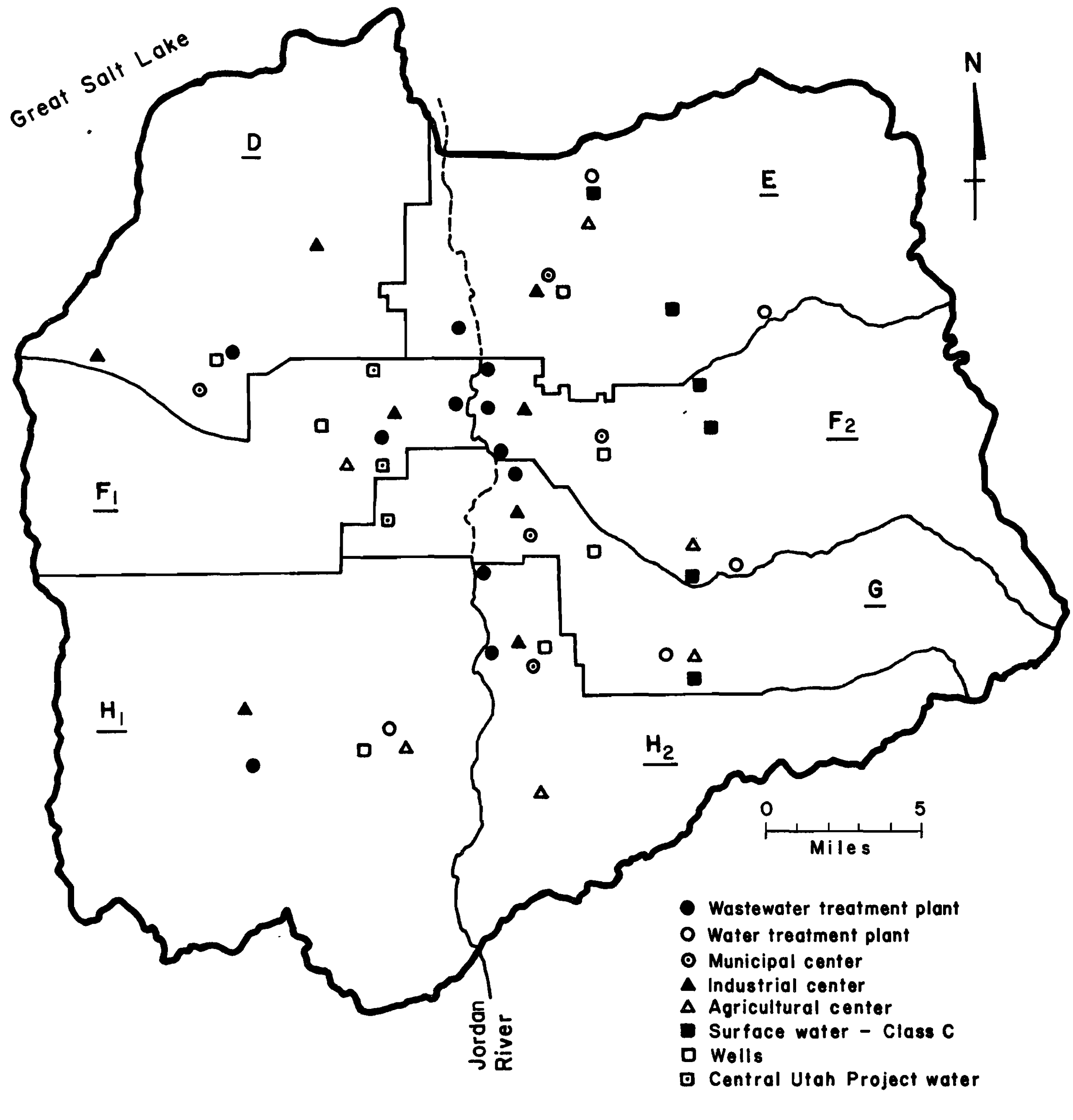


Figure A-1. Subregional division of Salt Lake County with activity centroids for water and wastewater reuse.

DESTINATIONS / SOURCES	WTP				H2					H1		
	C	[illegible]	UC	LC	M	I	A	TP1	TP2	M	I	A
CENTR. UT. PROJECT											4.5	
RB, E, P&C CREEK												
BC&M CREEK												
LC. CREEK												
SLC AQUIDUCT												
C												
MO												
BC												
LC												
JR. NARROWS			5									
H2 WELLS										6	10	5.5
H2 M	16	14	7	4						5.5	10	5
H2 I	15.5	13.5	15	5						5	9	15.5
H2 TP1	15.5	14.5	8.5	6								
H2 TP2	13.5	12.5	8.5	6.5								
UTAH LAKE DIST. C												
PROVO RES. CANAL												
H1 WELLS					6.5	6	6					
H1 M	19.5	13.5	12.5	9.5	5.5	5	5.5					
H1 I	21	2.5	16.5	14	10	9	10	8	9			
JR N. TO 9400 SO.												
G WELLS					4	4	6.5			9	10.5	8
G M	11.5	10.5	7	6.5	4.5	3.5	8.5	4	2	8	11	8
G I	11.5	10.5	7.5	6.5	4.5	4	9	4.5	2	8	11	8
G TP1	10	10	8	6	6.5	5.5	11			9.5	12	9.5
JR 94-5800 SO.												
F2 WELLS					7	7	12			12	14.5	12
F2 M	8.5	6.5	7	7.5	7.5	7.5	12	8	6	12	15	12
F2 I	8	8.5	9	8.5	8.5	7.5	12.5	8	3.5	11.5	13.5	12
F2 TP1	9.5	10	8.5	8.5	6.5	6	11			5.5	12	10
F2 TP2	8	10	10	10	8.5	8	13			11	13	11.5
F2 TP3	7	10	11	11	9.5	9	14			12.5	13.5	12.5
F1 WELLS					10.5	9.5	14			10	10	11
F1 M	11	13.5	12.5	12	9	8	13	7.5	5.5	9.5	10	10.5
F1 I	10	13	12.5	12	9.5	8.5	13.5	8	6	10.5	11	11
F1 TP1	8.5	10.5	10.5	10.5	8.5	8	13			11	12	11.5
JR 5800-2100 SO.		10										
E WELLS					12	14.5	17			15.5	17	16
E M	3.5	9.5	12.5	13	12.5	12	17	12.5	10	18	17.5	16
E I	4	8.5	12	13	12	11.5	16.5	12	9.5	15.5	17	17.5
E TP1	7	11.5	12.5	12.5	11	10	15			13	14	13.5
KENNECOTT PIPE												
D WELLS					11.5	13.5	18			13.5	11.5	14
D M	14.5	19.5	18.5	17.5	14.5	13.5	17.5	12.5	11	13	10.5	13.5
D I	12.5	23	22	21	17	16	20	15.5	12	15.5	12	16
D TP1	13.5	16.5	13	17.5	16.5	13.5	18			13.5	11.5	14
JR 2100 SO.-CUDDY												
WF OUTFLOW												
UT EFF OUTFLOW												

DESTINATIONS / SOURCES	G				F2						F1			
	M	I	A	TP1	M	I	A	TP1	TP2	TP3	M	I	A	TP1
CENTR. UT. PROJECT		4											1	
RB, E, P&C CREEK														
BC&M CREEK														
LC. CREEK														
SLC AQUIDUCT														
C														
MO														
BC														
LC														
JR. NARROWS														
H2 WELLS	4	4.5	5		7	8	6				8.9	9	8.5	
H2 M	4.5	5	5	6	8	8.5	6	6.9	8.9	10	9	9.5	9	8.5
H2 I	4	4	6	5.5	7.5	8	6.5	6	9	9	8	8.5	3	8
H2 TP1	4	4.5	7		8	8	7.5				7.5	8	7.5	
H2 TP2	1.5	2	7.5		8	8.5	7				5.5	6	5.5	
UTAH LAKE DIST. C														
PROVO RES. CANAL														
H1 WELLS	9	9	11		13	12	13				10	11	9.5	
H1 M	8	8	10.5	9.5	12	11.5	12	9.5	11.5	12.5	9.5	10.5	9	11
H1 I	11	11	15	12	15	13.5	15.5	12	13	13.5	10	11	9	12
JR N. TO 9400 SO.														
G WELLS					3.5	5	3.5				7.5	7.5	8	
G M					4	4	5.5	2.5	4	5.5	5.5	5.5	6	4.5
G I					4	3.5	6	2	3.5	5	5	5	5.5	4
G TP1					3.5	2	6.5				4.5	4	5	
JR 94-5800 SO.														
F2 WELLS	4	4	7.5								7.5	7	8.5	
F2 M	4	4	8	3							7	7	8	4.5
F2 I	4	3.5	10	2							4.5	4	6	2
F2 TP1	2.5	2	9								4	3.5	5	
F2 TP2	4	3.5	10.5								4.5	3	5	
F2 TP3	5.5	5	11.5								4	3	5.5	
F1 WELLS	7.5	7	14.5		9	6.5	13							
F1 M	5.5	5	12.5	4.5	7.5	4.5	11	4	3.5	4				
F1 I	5.5	5	12.5	4	7	4	11	3.5	3	3.5				
F1 TP1	4.5	4	11		4.5	2	9							
JR 5800-2100 SO.														
E WELLS	8	7.5	13		5	4	9.5				7.5	7	8	
E M	8.5	8	13.5	6.5	5.5	4.5	10	6	4.5	3.5	7.5	6.5	9	5
E I	8	7.5	13	6	5	4	10	9.5	4	3	7	6	8.5	4.5
E TP1	6.5	6	13		5.5	3	10				4	3	5	
KENNECOTT PIPE														
D WELLS	11.5	11	18.5		13	10	17				6	6	5.5	
D M	11.5	11	13.5	10.5	13.5	10.5	17	10	9.5	9.5	6	6.5	5.5	8.5
D I	15	14.5	22	13.5	16.5	15.5	20.5	13.5	13	12.5	9.5	9.5	9	12
D TP1	11.5	11	18.5		13	10	17				6	6	5.5	
JR 2100 SO.-CUDDY														
WF OUTFLOW														
UT EFF OUTFLOW														

DESTINATIONS / SOURCES	E				D				WT[illegible]			RHS
	M	I	A	TP1	M	I	A	TP1				
CENTR. UT. PROJECT						8.5	4					
RB, E, P&C CREEK												
BC&M CREEK												
LC. CREEK												
SLC AQUIDUCT												
C												
MO												
BC												
LC												
JR. NARROWS												
H2 WELLS	12.5	12	14		12	17	15					
H2 M	12.5	12	13.5	10.5	12	17	15.5	14.5				
H2 I	12	11.5	14	10	13.5	16.5	14.5	13.5				
H2 TP1	12.5	12	14.5		12.5	15.5	14.5					
H2 TP2	10	9.5	12		11	14	12					
UTAH LAKE DIST. C												
PROVO RES. CANAL												
H1 WELLS	16	16	19		13	15	16					
H1 M	16	15.5	18	17	13	15.5	16.5	13.5				
H1 I	17.5	17	20	14	10.5	12	15.5	12				
JR N. TO 9400 SO.												
G WELLS	9	8.5	10.5		12	16.5	13.5					
G M	8.5	8	10.5	6.5	11.5	14.5	11.5	11				
G I	8	7.5	10	6	11	14.5	11.5	11				
G TP1	6.5	6	9		10.5	14	10					
JR 94-5800 SO.												
F2 WELLS	6	5.5	7.9		3.5	16.5	11.5					
F2 M	5.5	5	7	5.5	13	16.5	11	12.5				
F2 I	4.5	4	6.5	3	10.5	13.5	8.5	10				
F2 TP1	6	3.5	8.5		10	13.5	9.5					
F2 TP2	4.5	4	7		9.5	12.5	8					
F2 TP3	3.5	3	6		9.5	12.5	7					
F1 WELLS	9	9.5	11		4	7.5	6					
F1 M	7.5	7	10	4	6	9.5	6.5	5.5				
F1 I	6.5	6	9	3	6.5	9.5	6	6				
F1 TP1	5	4.5	7.5		8.5	12	7					
JR 5800-2100 SO.												
E WELLS					12	15.9	8					
E M					12	15	7.5	11				
E I					11.5	14.5	7.5	10.5				
E TP1					8.5	11.5	6					
KENNECOTT PIPE												
D WELLS	11	11	13									
D M	12	11.5	14	8.5								
D I	15	14.5	17	11.5								
D TP1	11	11	13									
JR 2100 SO.-CUDDY												
WF OUTFLOW												
UT EFF OUTFLOW												

Figure A-2. Interdistrict transportation distances (in miles).

Raw sewage transmission costs

The costs and methods of transporting wastewater are dependent upon the cost of the pipe, cost of lift stations or pump stations, transmission distance, slope of terrain, cost of right-of-way, and the required capacity. Three possible conditions exist: a) gravity sewers alone, b) gravity sewers plus lift station, and c) force main plus pump station. These conditions are designated by sewer slope limits, and are only approximate.

A. Pump and lift stations

(1) Power costs (Bishop et al., 1974, p. 45)
$y = 28.8\ Q^{0.897}\ H$ (1970 prices)
$y = 31.7\ Q^{0.897}\ H$ (10% increase)
$y = 0.0584\ x^{0.897}\ H$
where y = Dollars
Q = mgd
x = AF/YR
H = Feet of pump lift

(2) Capital (Klemetson, 1974, p. 75)
$y = 128{,}000\ Q^{0.615}$ (Total cost)
$y = 16{,}640\ Q^{0.615}$ (CRF-5 1/2-10)
$y = 222\ x^{0.615}$

(3) O & M (Klemetson, 1974, p. 75)
$y = 1800\ Q^{0.644}$
$y = 19.6\ x^{0.644}$

(4) Summary pump station
a) Power costs - $y = 0.0584\ x^{0.897}\ H$
b) O & M costs - $y = 19.6\ x^{0.644}$
c) Capital - $y = 222\ x^{0.615}$
d) Equation

$$y = 241\ x^{0.618}\ N + 0.0584\ x^{0.897}\ H \qquad \text{(Cost 98)}$$

where y = Dollars
N = Number of lift station (400 ft. max. lift)
x = AF/YR
H = Feet of pump lift

B. Gravity trunk sewer

It was assumed that the O & M costs are equal to 10 percent of annual capital costs.

(1) Capital (Klemetson, 1974, Table 14)
$y = 287{,}000\ Q^{0.359}\ L$ (Total cost)
$y = 17{,}220\ Q^{0.359}\ L$ (CRF-5 1/2-50)
$y = 1{,}385\ x^{0.359}\ L$
where y = Dollars
Q = mgd
L = Length in miles
x = AF/YR

(2) O & M
$y = 138\ x^{0.359}\ L$

(3) Total

$$y = 1{,}523\ x^{0.359}\ L \qquad \text{(Cost 99)}$$

where y = Dollars
x = AF/YR
L = Length in miles

C. Force mains

It was assumed that O & M costs are equal to 10 percent of annual capital costs.

(1) Capital (Klemetson, 1974, Table 14)
$y = 103{,}000\ Q^{0.463}\ L$ (Engineering-Science, Inc., 1970)
$y = 6{,}180\ Q^{0.463}\ L$ (CRF-5 1/2-50)
$y = 239\ x^{0.463}\ L$
where y = Dollars
Q = mgd
L = Length in miles
x = AF/YR

(2) O & M
$y = 23.9\ x^{0.463}\ L$

(3) Total
$y = 263\ x^{0.463}\ L$ (Cost 100)
where y = Dollars
x = AF/YR
L = Length in miles

D. Summary

(1) Pump and lift stations
$y = 241\ x^{0.618}\ N + 0.0584\ x^{0.897}\ H$ (See Cost 98)

(2) Gravity trunk sewers
$y = 1{,}523\ x^{0.359}\ L$ (See Cost 99)

(3) Force mains
$y = 263\ x^{0.463}\ L$ (See Cost 100)

(4) where y = Dollars
x = AF/YR
N = Number of lift stations (max. 400 ft. lift per station)
H = Feet of pump lift
L = Length in miles

APPENDIX B
Optimal Solutions for the Various Model Formulations

SOURCES \ DESTINATION	C	MD	BC	LC	H_2 M	H_2 I	H_2 A	H_2 TP_1	H_2 TP_2	H_1 M	H_1 I	H_1 A	G M	G I	G A	G TP_1	F_2 M	F_2 I	F_2 A	F_2 TP_1	F_2 TP_2	F_2 TP_3	F_1 M	F_1 I	F_1 A	F_1 TP_1	E M	E I	E A	E TP_1	D M	D I	D A	D TP_1	UT EFF	WF	JR CD	RHS
CENTRAL UTAH PROJ																																						≤ 3,000
RB, E, P & C CREEKS		30.3																										8.9										= 33,200
BC & M CREEKS			42.6																																		20.8	= 63,400
LC CREEK				33.8		5.8																														9.5		= 49,100
SLC AQUEDUCT				14.5																																		= 14,500
C																																						≤ 19,100
MD																											30.3											≤ 35,900
BC													22.9														19.7											≤ 42,600
LC					9.1					4.2							25.7						6.4								2.8	.1						≤ 112,100
JR NARROWS							42.1					90.5							5.5														15.1			18.1	35	= 206,300
H_2 WELLS																																						≤ 1,900
H_2 M								4.5																														= 4,500
H_2 I									.2																													= 200
H_2 TP_1																																				4.5		≤ 4,500
H_2 TP_2																																				1.3	1.0	≤ 3,900
UTAH LAKE DIST. C														25.6																								≤ 25,600
PROVO RES. CANEL											3.4																											≤ 3,400
H_1 WELLS											.8																											≤ 1,300
H_1 M								2.1																														= 2,100
H_1 I																																						= 0
JR No to 9400 So.																																50.5						= 50,500
G WELLS															.2								8.1															≤ 8,300
G M																5.6																			5.7			= 11,300
G I																																						= 0
G TP_1																																				4.6	1.0	≤ 5,600
JR 94-5800 So.																									37.9							26.4						= 64,300
F_2 WELLS																		.4																				≤ 4,600
F_2 M																			8.7	4.0																		≤ 12,700
F_2 I																			.3																			= 300
F_2 TP_1																																						≤ 9,000
F_2 TP_2																																				9		≤ 17,900
F_2 TP_3																																				4		≤ 5,100
F_1 WELLS																									2.1													≤ 2,100
F_1 M																										7.1												= 7,100
F_1 I																																						= 0
F_1 TP_1																																				7.1		≤ 7,800
JR 5800-2100 So.																													2.9							1	59.2	= 63,100
E WELLS																												1.3										≤ 3,600
E M																														24.8								= 24,800
E I																														8.2								= 8,200
E TP_1																																				33		≤ 50,400
KENNECOTT PIPE																																9.5						≤ 9,500
D WELLS																																24.2						≤ 24,200
D M																																		1.4				= 1,400
D I																																			81.8			= 81,800
D TP_1																																				1.4		≤ 1,500
UNTR EFF OUTFLW																																			24.2			= 24,200
WF OUTFLOW																																					106.2	= 166,200
JR 2100 So - CUDAHY																																				87.5		≥ 0
	≥ 0	≥ 0	≥ 0	≥ 0	= 9,100	= 5,800	= 42,100	≥ 0	≥ 0	= 4,200	= 4,200	= 90,500	= 22,900	= 0	= 25,800	≥ 0	= 25,700	= 400	= 5,500	≥ 0	≥ 0	≥ 0	= 14,500	= 0	= 4,000	≥ 0	= 5,000	= 10,200	= 2,900	≥ 0	= 2,800	= 110,700	= 15,100	≥ 0	≥ 0	= 205,200	≥ 0	

Figure B-1. Linear costs, 7 subregion, annual model with deterministic water availabilities and secondary treatment.

DESTINATION / SOURCES					H2					H1			G				F2						F1				E				D								RHS
	C	MD	BC	LC	M	I	A	TP_1	TP_2	M	I	A	M	I	A	TP_1	M	I	A	TP_1	TP_2	TP_3	M	I	A	TP_1	M	I	A	TP_1	M	I	A	TP_1	UT EFF	WF	JR CD		
CENTRAL UTAH PROJ										13			57																										≤ 7,000
RB, E, P & C CREEKS		35.9																																		3.3			= 39,200
BC & M CREEKS			42.6														12.4	.4																		8			= 63,400
LC CREEK				49.1																																			= 49,100
SLC AQUEDUCT				14.5																																			= 14,500
C																																							≤ 19,100
MD																											35.9												≤ 35,900
BC													13.3														24				5.3								≤ 42,600
LC					29.8												33															.8							≤ 112,100
JR NARROWS						5.8	23.5					56.3													1.9								45.6	7.4		65.8			= 206,300
H2 WELLS					1.9																																		≤ 1,900
H2 M								2.1																				14.2											= 16,300
H2 I								.2																															= 200
H2 TP_1																																				2.3			≤ 4,500
H2 TP_2																																				3.9			≤ 3,900
UTAH LAKE DIST. C												1.6			5.8																								≤ 25,600
PROVO RES. CANEL											4.2																												≤ 6,200
H1 WELLS					1.3																																		≤ 1,300
H1 M									3.9	-		2.5																											= 6,400
H1 I																																							= 0
JR No. to 9400 So.																																24							= 2,400
G WELLS																							8.3																≤ 8,300
G M																																							= 34,800
G I																																			34.8				= 0
G TP_1																																							≤ 5,600
JR 94-5800 So.																																31.6							= 31,600
F2 WELLS																	4.6																						≤ 4,600
F2 M																				6.9	17.9																		= 24,800
F2 i																				.3																			= 300
F2 TP_1																																				7.2			≤ 9,000
F2 TP_2																																				17.9			≤ 17,900
F2 TP_3																																							≤ 5,100
F1 WELLS																							2																≤ 2,100
F1 M																									9.3	7.8													= 17,100
F1 I																																							= 0
F1 TP_1																									7.8														≤ 7,800
JR 5800-2100 So.																													1.2							28.6			= 29,800
E WELLS																											3.6												≤ 3,600
E M																														31.4									= 31,400
E I																														11.1									= 11,100
E TP_1																																				42.5			≤ 50,400
KENNECOTT PIPE																																9.5							≤ 9,500
D WELLS																							24.2																≤ 24,200
D M																																		1.5	1.5				= 3,000
D I																																			31.8				= 81,800
D TP_1																																				1.5			≤ 1,500
UNTR. EFF. OUTFLW																																				24.2			= 24,200
WF OUTFLOW																																					166.2		= 166,200
JR 2100 So - CUDAHY																																					118.1		≥ 0
	≥ 0	≥ 0	≥ 0	≥ 0	= 33,000	= 5,800	= 23,500	≥ 0	≥ 0	= 13,000	= 4,200	= 60,400	= 70,300	= 0	= 5,800	≥ 0	= 50,000	= 400	= 0	≥ 0	≥ 0	≥ 0	= 34,500	= 0	= 19,000	≥ 0	= 63,500	= 14,200	= 1,200	≥ 0	= 6,100	= 110,700	= 7,400	≥ 0	≥ 0	= 205,200	≥ 0		

Figure B-1. (Continued).

SOURCES \ DESTINATION					H2					H1			G				F2						F1				E				D							RHS
	C	MD	BC	LC	M	I	A	TP_1	TP_2	M	I	A	M	I	A	TP_1	M	I	A	TP_1	TP_2	TP_3	M	I	A	TP_1	M	I	A	TP_1	M	I	A	TP_1	UT EFF	WF	JR CD	RHS
CENTRAL UTAH PROJ																																						≤ 36,500
RB, E, P & C CREEKS		31.9																										7.3										= 39,200
BC & M CREEKS			42.6																																	.8	20	= 63,400
LC CREEK				43.3		5.8																																= 49,100
SLC AQUEDUCT				14.5																																		= 14,500
C																																						≤ 19,100
MD																											31.9											≤ 35,900
BC													26.9														15.7											≤ 42,600
LC					6.7					6.4							28.6						8.4				4.5				3.2							≤ 112,100
JR NARROWS							39.8					87.1							4.3						4.8								14			55.3	1.0	= 206,300
H2 WELLS					1.9																																	≤ 1,900
H2 M								4.5																	1.9													= 6,400
H2 I									.2																													= 200
H2 TP_1																																				6.5		≤ 4,500
H2 TP_2																																				2.6	1.0	≤ 3,900
UTAH LAKE DIST. C															22.1																							≤ 25,600
PROVO RES CANEL											4.2																											≤ 40,000
H1 WELLS					1.3																																	≤ 1,300
H1 M									3.2																													= 3,200
H1 I																																						= 0
JR No to 9400 So																																46						= 46,000
G WELLS																							8.3															≤ 8,300
G M																5.6																			7.7			=133,000
G I																																						= 0
G TP_1																																				4.6	1.0	≤ 5,600
JR 94-5800 So.																									30.0							31.0						= 61,000
F2 WELLS					3.0												.4																					≤ 4,600
F2 M																				8.7																		= 14,200
F2 I																					5.5																	= 300
F2 TP_1																				.3																		≤ 9,000
F2 TP_2																																				9.0		≤ 17,900
F2 TP_3																																				5.5		≤ 5,100
F1 WELLS																																						≤ 2,100
F1 M																										7.8									.5			≤ 8,300
F1 I																																						= 0
F1 TP_1																																				7.8		≤ 7,800
JR 5800-2100 So.																													2.2							55.3	1.0	= 58,500
E WELLS																												3.6										≤ 3,600
E M																																						= 25,800
E I																														25.8								= 8,500
E TP_1																														8.5						34.3		≤ 50,400
KENNECOTT PIPE																																9.5						≤ 9,500
D WELLS																																24.2						≤ 24,200
D M																																		1.5	1.0			= 1,600
D I																																			81.8			= 81,800
D TP_1																																				1.5		≤ 1,500
UNTR. EFF. OUTFLW																																				24.2		= 24,200
WF OUTFLOW																																					166.2	= 166,200
JR 2100 So-CUDAHY																																					90.1	≥ 0
	≥ 0	≥ 0	≥ 0	≥ 0	= 12,900	= 5,800	= 39,800	≥ 0	≥ 0	= 6,400	= 4,200	= 87,100	= 26,900	= 0	= 22,100	≥ 0	= 28,600	= 400	= 4,300	≥ 0	≥ 0	≥ 0	= 16,700	= 0	= 36,700	≥ 0	= 52,100	= 10,900	= 2,200	≥ 0	= 3,200	= 110,700	= 14,000	≥ 0	≥ 0	= 205,200	≥ 0	

Figure B-1. (Continued).

DESTINATION / SOURCES					H2					H1			G				F2						F1				E				D							RHS
	C	MD	BC	LC	M	I	A	TP1	TP2	M	I	A	M	I	A	TP1	M	I	A	TP1	TP2	TP3	M	I	A	TP1	M	I	A	TP1	M	I	A	TP1	UT EFF	WF	JR CD	
CENTRAL UTAH PROJ										9.8			43																									≤ 7,000
RB, E, P & C CREEKS		30.9																										8.4										= 39,200
BC & M CREEKS			42.6															.4																		20.4		= 63,400
LC CREEK				49.1																																		= 49,100
SLC AQUEDUCT				14.5																																		= 14,500
C																																						≤ 19,100
MD					5.3																						25.5											≤ 35,900
BC													2.5														35.5				4.6							≤ 42,600
LC					14.2												34.6						14.8															≤ 112,100
JR NARROWS						5.8	32.1					73.9							.6						8.4								6.5			55.4	19.6	= 206,300
H2 WELLS					1.9																														6.3			≤ 1,900
H2 M								4.3																														= 10,600
H2 I								.2																														= 200
H2 TP1																																				1	3.5	≤ 4,500
H2 TP2																																				1	2.9	≤ 3,900
UTAH LAKE DIST. C															12.8																							≤ 25,600
PROVO RES. CANEL											2.9																											≤ 52,500
H1 WELLS											1.3																											≤ 1,300
H1 M									3.9			1.0																										= 4,900
H1 I																																						= 0
JR No. to 9400 So.																																33.5						= 35,500
G WELLS																							8.3															≤ 8,300
G M																																			22.5			= 22,500
G I																																						= 0
G TP1																																						≤ 5,600
JR 94-5800 So.																									6.2							41.5						= 47,700
F2 WELLS																	4.6																					≤ 4,600
F2 M																				8.7	10.8																	= 19,500
F2 I																				.3																		= 300
F2 TP1																																				9		≤ 9,000
F2 TP2																																				10.8		≤ 17,900
F2 TP3																																						≤ 5,100
F1 WELLS																							2.1															≤ 2,100
F1 M																									4.7	7.8												= 12,500
F1 I																									7.8													= 0
F1 TP1																																						≤ 7,800
JR 5800-2100 So.																													1.7							42.3		= 44,000
E WELLS																												3.6										≤ 3,600
E M																																						= 30,200
E I																														30.2								= 9,400
E TP1																														9.4						39.6		≤ 50,400
KENNECOTT PIPE																																9.5						≤ 9,500
D WELLS																																24.2						≤ 24,200
D M																																		1.5	.8			= 2,300
D I																																			81.8			= 81,800
D TP1																																				1.5		≤ 1,500
UNTR. EFF. OUTFLW																																				24.2		= 24,200
WF OUTFLOW																																					166.2	= 166,200
JR 2100 So.-CUDAHY																																					111.4	≥ 0
	≥ 0	≥ 0	≥ 0	≥ 0	= 21,400	= 5,800	= 32,100	≥ 0	≥ 0	= 9,800	= 4,200	= 74,900	= 45,500	= 0	= 12,800	≥ 0	= 39,200	= 400	= 600	≥ 0	≥ 0	≥ 0	= 25,200	= 0	= 27,100	≥ 0	= 61,000	= 12,000	= 1,700	≥ 0	= 4,600	= 110,700	= 10,500	≥ 0	≥ 0	= 205,200	≥ 0	

Figure B-1. (Continued).

Figure B-1. (Continued).

DESTINATION / SOURCES	C	MD	BC	LC	H_2 M	H_2 I	H_2 A	H_2 TP_1	H_2 TP_2	H_1 M	H_1 I	H_1 A	G M	G I	G A	G TP_1	F_2 M	F_2 I	F_2 A	F_2 TP_1	F_2 TP_2	F_2 TP_3	F_1 M	F_1 I	F_1 A	F_1 TP_1	E M	E I	E A	E TP_1	D M	D I	D A	D TP_1	UT EFF	WF	JR CD	RHS
CENTRAL UTAH PROJ.										7.4			12.1																									≤ 70,000
PB, E, P & C CREEKS		31.5																										7.7										= 39,200
BC & M CREEKS			42.6																																	3.2	7.6	= 63,400
LC CREEK				45.2		3.9																																= 49,100
SLC AQUEDUCT				14.5																																		= 14,500
C																																						≤ 19,100
MD																											31.5											≤ 35,900
BC													18.4														24.2											≤ 42,600
LC					14.7												31.0						10.4								3.6							≤ 112,100
JR NARROWS							39.7					88							3.6														13.5			61.5		= 206,300
H_2 WELLS						1.9																																≤ 1,900
H_2 M								4.5																											2.8			= 7,300
H_2 I									.2																													= 200
H_2 TP_1																																				4.5		≤ 4,500
H_2 TP_2																																				3.9		≤ 3,900
UTAH LAKE DIST. C															20.5																							≤ 25,600
PROVO RES. CANEL											2.9																											≤ 45,500
H_1 WELLS											1.3																											≤ 1,300
H_1 M									3.7																													= 3,700
H_1 I																																						= 0
JR No to 9400 So																																44.4						≤ 44,400
G WELLS																							8.3															≤ 8,300
G M																																			15.1			= 15,100
G I																																						= 0
G TP_1																																						≤ 5,600
JR 94-5800 So.																									26.6							32.6						= 59,200
F_2 WELLS																		.4																				≤ 4,600
F_2 M																				8.7	6.7																	= 15,400
F_2 I																				.3																		= 300
F_2 TP_1																																				9.0		≤ 9,000
F_2 TP_2																																					6.7	≤ 17,900
F_2 TP_3																																						≤ 5,100
F_1 WELLS																									.1													≤ 2,100
F_1 M																									1.4	7.8												= 9,200
F_1 I																																						= 0
F_1 TP_1																									7.8													≤ 7,800
JR 5800-2100 So.																													2.2							54.3		= 56,500
E WELLS																												3.6										≤ 3,600
E M																														27.6								= 27,600
E I																														8.8								= 8,800
E TP_1																																				36.4		≤ 54,800
KENNECOTT PIPE																																9.5						≤ 9,500
D WELLS																																24.2						≤ 24,200
D M																																		1.5	.3			= 1,800
D I																																			31.8			= 81,800
D TP_1																																				1.5		≤ 1,500
UNTR. EFF. OUTFL'W																																				24.2		= 24,200
WF OUTFLOW																																					166.2	= 166,200
JR 2100 So - CUDAHY																																					100	≥ 0
	≥ 0	≥ 0	≥ 0	≥ 0	= 14,700	= 5,800	= 39,700	≥ 0	≥ 0	= 7,400	= 4,200	= 88,000	= 30,500	= 0	= 20,500	≥ 0	= 31,000	= 400	= 3,600	≥ 0	≥ 0	≥ 0	= 18,700	= 0	= 35,900	≥ 0	= 55,700	= 11,300	= 2,200	≥ 0	= 3,600	= 110,700	= 13,500	≥ 0	≥ 0	= 205,200	≥ 205,200	

YEAR : 1975
SEASON: Annual

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	1				5					10					15					20					25	
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)					0.4	71.3				10.0	0.2		30.6													
SW (E)										29.2	10.0															
Jor. R:H			132.6							114.2	10.0															
F										127.4																
E										24.2																
Imp W I>C		10.0						10.2																		
<C									2.9																	
GW: H	13.3																									
F				54.5																						
E							28.0																			
M&I Eff H														6.8												
F																	31.4									
E																				33.0						
WTP: C&E																										
BC&LC				8.6			22.0																			
WWTP H1										6.8																
2																										
3																										
WWTP F1										30.4	1.0															
2																										
3																										
WWTP E1										33.0																
2																										
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $13,424,369

Figure B-2. Nonlinear costs, three subregion, annual model with deterministic water availabilities and secondary treatment levels.

YEAR : 1980
SEASON: Annual

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)					0.4	63.1				7.2			41.8													
SW (E)										29.2	10.0															
Jor. R:H			126.9							115.4	10.0															
F										119.5																
E										24.2																
Imp.W1>C		10.0						10.9																		
<C									2.2																	
GW: H	19.3																									
F				54.5																						
E							28.0																			
M&I Eff H											1.4				8.4											
F																	36.1									
E																				34.3						
WTP: C&E																										
BC&LC				17.7			24.1																			
WWTP H1										8.4																
2																										
3																										
WWTP F1										35.1	1.0															
2																										
3																										
WWTP E1										34.3																
2																										
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $15, 094, 270

Figure B-2. (Continued).

YEAR : 1985
SEASON: Annual

1 5 10 15 20 25

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)						60.0							52.5													
SW (E)										29.2	10.0															
Jor. R:H			127.7							110.6	10.0															
F										111.8																
E										24.2																
Imp. Wt>C		10.0			0.4			11.3					1.7													
<C									2.2																	
GW: H	21.3																									
F				54.5																						
E							28.0																			
M&I Eff H											2.8			8.4												
F																	40.0									
E																				36.4						
WTP: C&E																										
BC & LC	0.8			25.7			27.7																			
WWTP H1										8.4																
2																										
3																										
WWTP F1										39.0	10.0															
2																										
3																										
WWTP E1																										
2										36.4																
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $16,469,237

Figure B-2. (Continued).

YEAR : 2000
SEASON: Annual

	1				5					10					15					20					25	
Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)						40.5							72.0													
SW (E)										29.2	10.0															
Jor. R:H			107.0							124.8	10.0															
F										91.7																
E										24.2																
Imp.W I>C		10.0			0.4			12.0					26.3													
<C									1.7																	
GW: H	21.3																									
F				54.5																						
E							28.0																			
M&IEff H											7.3			8.4												
F											9.4						45.4									
E																				39.6						
WTP: C&E																										
BC&LC	9.9			55.4			33.0																			
WWTP H1										8.4																
2																										
3																										
WWTP F1										44.6	1.0															
2																										
3																										
WWTP E1										39.6																
2																										
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $21,003,335

Figure B-2. (Continued).

YEAR : 2020
SEASON: Annual

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)						24.8							87.7													
SW (E)										16.3	10.0	12.9														
Jor. R:H			83.0							137.3	10.0															
F										61.4																
E										24.2																
Imp.W I>C		10.0			0.4			14.2					59.9													
<C									1.2																	
GW: H	21.3																									
F				54.5																						
E							28.0																			
M&I Eff H											22.9															
F											31.6						45.4									
E																				42.5						
WTP: C&E	12.9																									
BC&LC	11.8			100.3			35.5																			
WWTP H1																										
2																										
3																										
WWTP F1										44.4	1.0															
2																										
3																										
WWTP E1										42.5																
2																										
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $26, 795, 240

Figure B-2. (Continued).

YEAR : 1980
SEASON: Annual QL-2

1 5 10 15 20 25

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)						63.1				7.6			41.8													
SW (E)										29.2	10.0															
Jor. R:H			126.9							115.4	10.0															
F										119.5																
E										24.2																
Imp W1>C		10.0						10.9																		
<C									2.2																	
GW: H	19.3																									
F				54.5																						
E							28.0																			
M&IEff H															9.8											
F																	36.1									
E																				34.3						
WTP: C&E																										
BC&LC				17.7			24.1																			
WWTP H1																										
2										9.8																
3																										
WWTP F1																		36.1								
2					0.4					35.7																
3																										
WWTP E1																					34.3					
2										34.3																
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $16, 246, 516

Figure B-3. Nonlinear costs, three subregion, annual model with deterministic water availabilities and tertiary treatment levels.

YEAR : 1985
SEASON: Annual QL-3

Destinations/Sources	Area H M	Area H I	Area H A	Area F M	Area F I	Area F A	Area E M	Area E I	Area E A	BR	OF	WTP C&E	WTP BC&LC	WWTP H H1	WWTP H H2	WWTP H H3	WWTP F F1	WWTP F F2	WWTP F F3	WWTP E E1	WWTP E E2	WWTP E E3	Reg. WWTP R1	Reg. WWTP R2	Reg. WWTP R3	Reuse
SW (F)													112.5													
SW (E)								11.3		27.9																
Jor. R:H			127.7							110.6	10.0															
F										111.8																
E										24.2																
Imp WDC												22.1														
<C						60.0			2.2																	
GW: H																										
F																										
E							23.4																			
M&I Eff H														8.4	2.8											
F																									40.0	
E																									36.4	
WTP: C&E	22.1																									
BC&LC				80.2			32.3																			
WWTP H1															8.4											
2		10.0			0.4											0.8										
3										0.8																
WWTP F1																										
2																										
3																										
WWTP E1																										
2																										
3																										
Regional R1																										
2																										
3										75.4	1.0															
Reuse																										

Z = $21, 316, 827

Figure B-3. (Continued).

YEAR : 2000
SEASON: Annual QL-3

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)													112.5													
SW (E)								12.0				27.2														
Jor. R:H			107.0							124.8	10.0															
F										91.7																
E										24.2																
Imp.W I>C												55.0	6.6													
<C						40.5			1.7																	
GW: H																										
F					0.4																					
E							28.0																			
M&I Eff H														8.4	7.3											
F																									54.8	
E																									39.6	
WTP: C&E	31.2						23.8																			
BC&LC				109.9			9.2																			
WWTP H1															8.4											
2		10.0														5.7										
3										5.7																
WWTP F1																										
2																										
3																										
WWTP E1																										
2																										
3																										
Regional R1																										
2																										
3										93.4	1.0															
Reuse																										

Z = $26, 312, 416

Figure B-3. (Continued).

YEAR : 2020
SEASON: Annual QL-3

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
	1				5					10					15					20					25	
SW (F)													112.5													
SW (E)								14.2		25.0																
Jor. R:H			83.0							137.3	10.0															
F										61.4																
E										24.2																
Imp W >C												55.0	29.5													
<C						24.8			1.2																	
GW: H	21.3																									
F				18.0	0.4																					
E							28.0																			
M&I Eff H															22.9											
F																									77.0	
E																									42.5	
WTP: C&E	24.7						30.3																			
BC&LC				136.8			5.2																			
WWTP H1																										
2		10.0														12.9										
3										12.9																
WWTP F1																										
2																										
3																										
WWTP E1																										
2																										
3																										
Regional R1																										
2																										
3										118.5	1.0															
Reuse																										

Z = $32, 553, 185

Figure B-3. (Continued).

YEAR : 1975
SEASON: Winter

	1				5					10					15					20					25	
Destinations/Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)										19.3																
SW (E)								5.1		3.2																
Jor. R:H										52.1	10.0															
F										22.6																
E										4.9																
Imp. W D>C												7.4														
<C																										
GW: H		5.0																								
F				21.3	0.2																					
E							14.0																			
M&I Eff H														2.1												
F																	9.7									
E																				11.7						
WTP: C&E	4.5						2.9																			
BC&LC																										
WWTP H1										2.1																
2																										
3																										
WWTP F1										8.7	1.0															
2																										
3																										
WWTP E1										11.7																
2																										
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $5, 144, 819

Figure B-4. Nonlinear costs, three subregion, seasonal model with deterministic water availabilities and secondary treatment levels.

YEAR : 1980
SEASON: Summer

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	1				5					10					15					20					25	
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)					0.2	63.1				0.8			23.3													
SW (E)								5.5		21.2																
Jor. R:H			126.9							89.8	10.0															
F										107.0																
E										18.1																
Imp.W1>C		5.0										27.5														
<C									2.2																	
GW: H	8.5																									
F				27.3																						
E							14.0																			
M&IEff H														3.1												
F																	11.5									
E																				12.5						
WTP: C&E	5.0						22.5																			
BC&LC				23.3																						
WWTPH1										3.1																
2																										
3																										
WWTPF1										10.5	1.0															
2																										
3																										
WWTPE1										12.5																
2																										
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $8,727,522

Figure B-4. (Continued).

YEAR : 1985
SEASON: Winter

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	1 M	I	A	M	5 I	A	M	I	A	10		C&E	BC&LC	H1	15 H2	H3	F1	F2	F3	20 E1	E2	E3	R1	R2	25 R3	
SW (F)					0.10					19.2																
SW (E)								5.7		2.6																
Jor. R:H										50.7	10.0															
F										20.0																
E										4.9																
Imp. W t>C												12.4														
<C																										
GW: H		5.0																								
F				27.4	0.1																					
E							14.0																			
M&I Eff H														3.5												
F																	12.3									
E																				12.9						
WTP: C&E	7.5						4.9																			
BC&LC																										
WWTP H1										3.5																
2																										
3																										
WWTP F1										10.0	2.3															
2																										
3																										
WWTP E1										12.9																
2																										
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $6,137,658

Figure B-4. (Continued).

YEAR : 1985
SEASON: Summer

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)						60.0							27.4													
SW (E)								5.7		21.0																
Jor. R:H			127.7							88.2	10.0															
F										105.4																
E										18.1																
Imp.W1>C		5.0			0.2							27.5	3.8													
<C									2.2																	
GW: H	10.7																									
F				27.3																						
E							14.0																			
M&IEff H														3.6												
F																	12.8									
E																				13.2						
WTP: C&E	2.5						25.0																			
BC&LC	2.3			28.9																						
WWTPH1										3.6																
2																										
3																										
WWTPF1										11.8	1.0															
2																										
3																										
WWTPE1										13.2																
2																										
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $9,478,725

Figure B-4. (Continued).

YEAR : 2000
SEASON: Winter

	1				5					10					15					20					25	
Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)					0.2					19.1																
SW (E)								6.0		2.3																
Jor. R:H										49.3	10.0															
F										15.4																
E										6.9																
Imp. W I>C												27.4														
<C																										
GW: H		5.0																								
F				27.2																						
E							14.0																			
M&I Eff H											4.9															
F																	16.9									
E																				14.0						
WTP: C&E	10.6			10.1			6.7																			
BC & LC																										
WWTP H1																										
2																										
3																										
WWTP F1										10.0	6.9															
2																										
3																										
WWTP E1										14.0																
2																										
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $7, 652, 721

Figure B-4. (Continued).

YEAR : 2000
SEASON: Summer

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	1				5					10					15					20					25	
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)						40.5							46.9													
SW (E)								6.0		20.7																
Jor. R:H			107.0							103.1	10.0															
F										91.6																
E										18.1																
Imp W>C		5.0			0.2							27.5	15.3													
<C									1.7																	
GW: H	10.7																									
F				27.3																						
E							14.0																			
M&IEff H											0.8			4.2												
F																	17.5									
E																				14.3						
WTP: C&E							27.5																			
BC&LC	11.2			49.8			1.2																			
WWTP H1										4.2																
2																										
3																										
WWTP F1										16.5	1.0															
2																										
3																										
WWTP E1										14.3																
2																										
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $11, 634, 685

Figure B-4. (Continued).

YEAR : 2020

1 5 10 SEASON: Winter 15 MOD 20 ZB = RPROBW 5 25

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)				15.1	0.2					4.0																
SW (E)								7.1			1.2															
Jor. R:H										47.1	10.0															
F										8.6																
E										4.9																
Imp. W1>C												27.5														
<C																										
GW: H	5.6	5.0																								
F				27.2																						
E							14.0																			
M&I Eff H											7.1															
F											1.0						22.7									
E																				15.2						
WTP: C&E	9.9			10.1			7.5																			
BC&LC																										
WWTP H1																										
2																										
3																										
WWTP F1										21.7	1.0															
2																										
3																										
WWTP E1										15.2																
2																										
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $10, 503, 537

Figure B-4. (Continued).

YEAR : 2020
SEASON: Summer

	1				5					10					15					20					25
Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)						24.8							62.6													
SW (E)							26.7																			
Jor. R:H			83.9							119.5	10.0															
F										75.9																
E										18.1																
Imp.W I>C		5.0		1.4	0.2			7.1				27.5	14.8													
<C									1.2																	
GW: H	10.7																									
F				27.3																						
E							14.0																			
M&I Eff H											3.1			4.2												
F											1.8						22.7									
E																				15.6						
WTP: C&E	21.5			2.2			3.8																			
BC&LC				77.4																						
WWTP H1										4.2																
2																										
3																										
WWTP F1										21.7	1.0															
2																										
3																										
WWTP E1										15.6																
2																										
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $15, 684, 931

Figure B-4. (Continued).

YEAR : 1980 QL-2
SEASON: Winter

	1				5					10					15						20				25	
Destinations/Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)										19.3																
SW (E)											8.3															
Jor. R:H										51.2	10.0															
F										21.2																
E										4.9																
Imp W I>C		5.0			5.5								3.6													
<C																										
GW: H	6.5																									
F				24.4																						
E							14.0																			
M&I Eff H															3.0											
F																	11.1									
E																				12.1						
WTP: C&E																										
BC&LC							3.6																			
WWTP H1																										
2										3.0																
3																										
WWTP F1																		11.1								
2					0.2					10.9																
3																										
WWTP E1																					12.1					
2										12.1																
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $6, 217, 681

Figure B-5. Nonlinear costs, three subregion, seasonal model with deterministic water availabilities and tertiary treatment levels.

YEAR : 1980
SEASON: Summer
QL-2

	1				5					10					15					20					25	
Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)						63.1							24.3													
SW (E)										16.7	10.0															
Jor. R:H			126.9							89.8	10.0															
F										107.0																
E										181.0																
Imp. W I>C		4.2						5.5					24.3													
<C									2.2																	
GW: H	10.7																									
F				27.3																						
E							14.0																			
M&I Eff H															3.1											
F																	11.5									
E																				12.5						
WTP: C&E																										
BC&LC	2.8			23.3			22.5																			
WWTP H1																										
2		0.8								2.3																
3																										
WWTP F1																		11.5								
2					0.2					11.3																
3																										
WWTP E1																					12.5					
2										12.5																
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $9,325,579

Figure B-5. (Continued).

YEAR : 1985
SEASON: Winter
QL-3

	1				5					10					15					20					25	
Destinations/Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)					0.1					19.2																
SW (E)								5.7		2.6																
Jor. R:H										50.7	10.0															
F										20.0																
E										4.9																
Imp. W t>C												12.4														
<C																										
GW: H		1.5																								
F				27.1	0.1																					
E							14.0																			
M&I Eff H														3.5												
F																									12.3	
E																									12.9	
WTP: C&E	7.5						4.9																			
BC & LC																										
WWTP H1															3.5											
2		3.5																								
3																										
WWTP F1																										
2																										
3																										
WWTP E1																										
2																										
3																										
Regional R1																										
2																										
3										24.2	1.0															
Reuse																										

Z = $8,492,097

Figure B-5. (Continued).

YEAR : 1985
SEASON: Summer QL-3

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	1				5					10					15					20					25	
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)										9.0	1.0		77.4													
SW (E)								5.7		21.0																
Jor. R:H			127.7							88.2	10.0															
F										105.4																
E										18.1																
Imp.W t>C												15.5														
<C						60.0			2.2																	
GW: H		1.4																								
F				3.8	0.2																					
E							14.0																			
M&I Eff H														3.6												
F																									12.8	
E																									13.2	
WTP: C&E	15.5																									
BC&LC				52.4			25.0																			
WWTP H1															3.6											
2																										
3		3.6																								
WWTP F1																										
2																										
3																										
WWTP E1																										
2																										
3																										
Regional R1																										
2																										
3										25.0	1.0															
Reuse																										

Z = $11, 580, 331

Figure B-5. (Continued).

YEAR : 2000

SEASON: Winter

QL-3

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	1				5					10					15					20					25	
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)					0.2					19.1																
SW (E)								6.0		2.3																
Jor. R:H										49.3	10.0															
F										15.4																
E										4.9																
Imp.W t>C												27.4														
<C																										
GW: H		0.1																								
F				27.2																						
E							14.0																			
M&I Eff H														4.2	0.7											
F																									16.9	
E																									14.0	
WTP: C&E	10.6			10.1			6.7																			
BC&LC																										
WWTP H1															4.2											
2		4.9																								
3																										
WWTP F1																										
2																										
3																										
WWTP E1																										
2																										
3																										
Regional R1																										
2																										
3										29.9	1.0															
Reuse																										

Z = $10, 234, 009

Figure B-5. (Continued).

YEAR : 2000
SEASON: Summer
QL-3

Destinations/Sources	Area H (1)			Area F (5)			Area E			BR (10)	OF	WTP		WWTP H (15)			WWTP F			WWTP E (20)			Reg. WWTP		(25)	Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)										9.0	1.0		77.4													
SW (E)								6.0		20.7																
Jor. R:H			107.0							103.1	10.0															
F										91.6																
E										18.1																
Imp.W1>C					0.2							23.0														
<C						40.5			1.9																	
GW: H																										
F				27.3																						
E							14.0																			
M&I Eff H														4.2	0.8											
F																									17.5	
E																									14.3	
WTP: C&E	21.9						1.1																			
BC&LC				49.8			27.6																			
WWTP H1															4.2											
2		5.0																								
3																										
WWTP F1																										
2																										
3																										
WWTP E1																										
2																										
3																										
Regional R1																										
2																										
3										30.8	1.0															
Reuse																										

Z = $13, 967, 977

Figure B-5. (Continued).

YEAR : 2020
SEASON: Winter
QL-3

1 5 10 15 20 25

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)													19.3													
SW (E)								7.1		1.2																
Jor. R:H										47.1	10.0															
F										8.6																
E										4.9																
Imp. W t>C					0.2							27.5	0.4													
<C																										
GW: H	1.0																									
F				27.2																						
E							14.0																			
M&I Eff H														4.2	2.9										23.7	
F																									15.2	
E																										
WTP: C&E	14.5			5.5			7.5																			
BC&LC				19.7																						
WWTP H1															4.2											
2		5.0														2.1										
3										2.1																
WWTP F1																										
2																										
3																										
WWTP E1																										
2																										
3																										
Regional R1																										
2																										
3										37.9	1.0															
Reuse																										

Z = $12, 946, 387

Figure B-5. (Continued).

YEAR : 2020
SEASON: Summer
QL-3

	1				5					10				15					20					25	
Destina-tions/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)				28.1									59.3													
SW (E)								7.1		19.6																
Jor. R:H			83.9							119.5	10.0															
F										75.9																
E										18.1																
Imp.W1>C					0.2							27.5	18.1													
<C						24.8			1.2																	
GW: H	10.7																									
F				27.3																						
E							14.0																			
M&I Eff H														4.2		3.1										
F																									24.5	
E																									15.6	
WTP: C&E	21.5						6.0																			
BC&LC				52.9			24.5																			
WWTP H1															4.2											
2		4.2																								
3		0.8								2.3																
WWTP F1																										
2																										
3																										
WWTP E1																										
2																										
3																										
Regional R1																										
2																										
3										39.1	1.0															
Reuse																										

Z = $18, 958, 717

Figure B-5. (Continued).

YEAR : 1975 L-1 Stochastic
SEASON: Annual

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	1				5					10					15					20					25	
	M	I	A	M	I	A	M	I	A			C&E	BC&IC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)						14.6							25.8													
SW (E)										21.0																
Jor. R:H			132.6							114.2	10.0															
F										127.4																
E										24.2																
Imp. W>C		10.0			0.4			10.2					4.8													
<C						56.7			2.9																	
GW: H	13.3																									
F				54.5																						
E							28.0																			
M&I Eff H														6.8												
F																	31.4									
E																				33.0						
WTP: C&E																										
BC&IC				8.6			22.0																			
WWTP H1										6.8																
2																										
3																										
WWTP F1										30.4	1.0															
2																										
3																										
WWTP E1										33.0																
2																										
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $13, 574, 050

Figure B-6. Nonlinear costs, three subregion,annual model with stochastic water availabilities and secondary treatment levels.

YEAR : 1980
SEASON: Annual
L-1
Stochastic

Destinations/Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)													40.4													
SW (E)												21.0														
Jor. R:H			126.9							115.4	10.0															
F										119.5																
E										24.2																
Imp.W I>C		10.0			0.4			10.9					1.4													
<C						63.1			2.2	0.3																
GW: H	19.3																									
F				54.5																						
E							28.0																			
M&IEff H											1.4			8.4												
F																	36.1									
E																				34.3						
WTP: C&E																										
BC&LC				17.7			24.1																			
WWTPH1										8.4																
2																										
3																										
WWTPF1										35.1	1.0															
2																										
3																										
WWTPE1										34.3																
2																										
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $15, 130, 463

Figure B-6. (Continued).

YEAR : 1985
SEASON: Annual L-1 Stochastic

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	1				5					10				15						20					25	
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)													40.4													
SW (E)										21.0																
Jor. R:H			127.7							110.6	10.0															
F										111.8																
E										24.2																
Imp W1>C		10.0			0.4			11.3					13.8													
<C						60.0			2.2	1.0																
GW: H	21.3																									
F				54.5																						
E							28.0																			
M&I Eff H											2.8			8.4												
F																	40.0									
E																				36.4						
WTP: C&E																										
BC&LC	0.8			25.7			27.7																			
WWTP H1										8.4																
2																										
3																										
WWTP F1										39.0	1.0															
2																										
3																										
WWTP E1										36.4																
2																										
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $16, 539, 771

Figure B-6. (Continued).

YEAR : 2000 L-1 Stochastic
SEASON: Annual

Destinations/ Sources	Area H M (1)	Area H I	Area H A	Area F M	Area F I (5)	Area F A	Area E M	Area E I	Area E A	BR (10)	OF	WTP C&E	WTP BC&LC	WWTP H H1	WWTP H H2 (15)	WWTP H H3	WWTP F F1	WWTP F F2	WWTP F F3	WWTP E E1 (20)	WWTP E E2	WWTP E E3	Reg. WWTP R1	Reg. WWTP R2	Reg. WWTP R3 (25)	Reuse
SW (F)					0.4						4.2		35.8													
SW (E)										21.0																
Jor. R:H			107.0							124.8	10.0															
F										91.1																
E										24.2																
Imp. Wt >C		10.0						12.0					62.5													
<C						40.5			1.7	1.0																
GW: H	21.3																									
F				54.5																						
E							28.0																			
M&I Eff H											7.3			8.4												
F											9.4						45.4									
E																				39.6						
WTP: C&E																										
BC&LC	9.9			55.4			33.0																			
WWTP H1										8.4																
2																										
3																										
WWTP F1										44.4	1.0															
2																										
3																										
WWTP E1										39.6																
2																										
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $21,057,251

Figure B-6. (Continued).

YEAR : 2020
SEASON: Annual L-1 Stochastic

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	1				5					10				15						20					25	
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)					0.4								40.0													
SW (E)								14.2				6.8														
Jor. R:H		10.0	83.0							127.3	10.0															
F										61.4																
E										24.2																
Imp. W I>C													84.5													
<C						24.8			1.2	1.0			29.0													
GW: H	21.3																									
F				54.5																						
E							28.0																			
M&I Eff H											22.9															
F											31.6						45.4									
E																				42.5						
WTP: C&E	6.8																									
BC&LC	17.9			100.3			35.5																			
WWTP H1																										
2																										
3																										
WWTP F1										44.4	1.0															
2																										
3																										
WWTP E1										42.5																
2																										
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $27,648,835

Figure B-6. (Continued).

YEAR : 1980
SEASON: Annual L-2 Stochastic

Destinations/ Sources	Area H (1)			Area F (5)			Area E			BR (10)	OF	WTP		WWTP H (15)			WWTP F			WWTP E (20)			Reg. WWTP		(25)	Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)						40.4																				
SW (E)										21.0																
Jor. R:H			126.9							115.4	10.0															
F										119.5																
E										24.2																
Imp.W t>C													41.8													
<C									2.2																	
GW: H	19.3	0.2																								
F				54.5																						
E							28.0																			
M&I Eff H															9.8											
F																	36.1									
E																										
WTP: C&E																				34.3						
BC & LC				17.7			24.1																			
WWTP H1																										
2		9.8																								
3																										
WWTP F1																		36.1								
2					0.4	22.7				13.0																
3																										
WWTP E1																										
2								10.9		23.4																
3																										
Regional R1																										
2																										
3																										
Reuse																										

Z = $16, 229, 696

Figure B-7. Nonlinear costs, three subregion, annual model with stochastic water availabilities and tertiary treatment levels.

YEAR : 1985
SEASON: Annual

QL-3 Stochastic

	1				5					10					15					20					25	
Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)													40.4													
SW (E)								11.3		9.7																
Jor. R:H			127.7							110.6	10.0															
F										111.8																
E										24.2																
Imp. W I>C												55.0	29.5													
<C						60.0			2.2																	
GW: H																										
F				10.3	0.4																					
E							22.8																			
M&I Eff H															11.2											
F																									40.0	
E																									36.4	
WTP: C&E	22.1						32.9																			
BC&LC				70.0																						
WWTP H1																										
2		10.0														1.2										
3										1.2																
WWTP F1																										
2																										
3																										
WWTP E1																										
2																										
3																										
Regional R1																										
2																										
3										75.4	1.0															
Reuse																										

Z = $22,000,385

Figure B-7. (Continued).

YEAR : 2000
SEASON: Annual

QL-3 Stochastic

	1				5					10					15					20					25	
Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)													40.4													
SW (E)								12.0		9.0																
Jor. R:H			107.0							124.8	10.0															
F										91.7																
E										24.2																
Imp.W I>C												55.0	29.5													
<C						40.5			1.7																	
GW: H																										
F				49.2	0.4																					
E							28.0																			
M&I Eff H															15.7											
F																									54.8	
E																									39.6	
WTP: C&E							33.0																			
BC&LC	9.2			60.7																						
WWTP H1																										
2		10.0														5.7										
3										5.7																
WWTP F1																										
2																										
3																										
WWTP E1																										
2																										
3																										
Regional R1																										
2																										
3										93.4	1.0															
Reuse																										

Z = $26,763,911

Figure B-7. (Continued).

YEAR : 2020
SEASON: Annual

QL-3 Stochastic

Destinations/ Sources	Area H			Area F			Area E			BR	OF	WTP		WWTP H			WWTP F			WWTP E			Reg. WWTP			Reuse
	1				5					10				15						20					25	
	M	I	A	M	I	A	M	I	A			C&E	BC&LC	H1	H2	H3	F1	F2	F3	E1	E2	E3	R1	R2	R3	
SW (F)					0.4								40.0													
SW (E)								14.2				6.8														
Jor. R:H			83.0							137.3	10.0															
F										61.4																
E										24.2																
Imp.W I>C												48.2	36.3													
<C						24.8			1.2				29.2													
GW: H	21.3																									
F				54.5																						
E							28.0																			
M&IEff H															22.9											
F																									77.0	
E																									42.5	
WTP: C&E	19.5						35.5																			
BC&LC				100.3																						
WWTP H1																										
2		10.0														12.9										
3										12.9																
WWTP F1																										
2																										
3																										
WWTP E1																										
2																										
3																										
Regional R1																										
2																										
3										118.5	1.0															
Reuse																										

Z = $33, 611, 693

Figure B-7. (Continued).

APPENDIX C

Program SEP is written with capability to produce data file with compatible format to be used with Burroughts TEMPO Separable Programming package at the USU computer center.

Data file gnerated has TEMPO data name 'REUSE', objective function name 'COST' and right hand side name 'BVECT "I"' where I is the suffix that can be raised from I to N depending on number of RHS vectors considered.

The undesirable allocation variables can be excluded by given certain cost function structure. (See user instruction part.)

Input cost functions can be only of type ax^b, and up to 5 functions can be accepted by the program for any particular use.

User Instruction

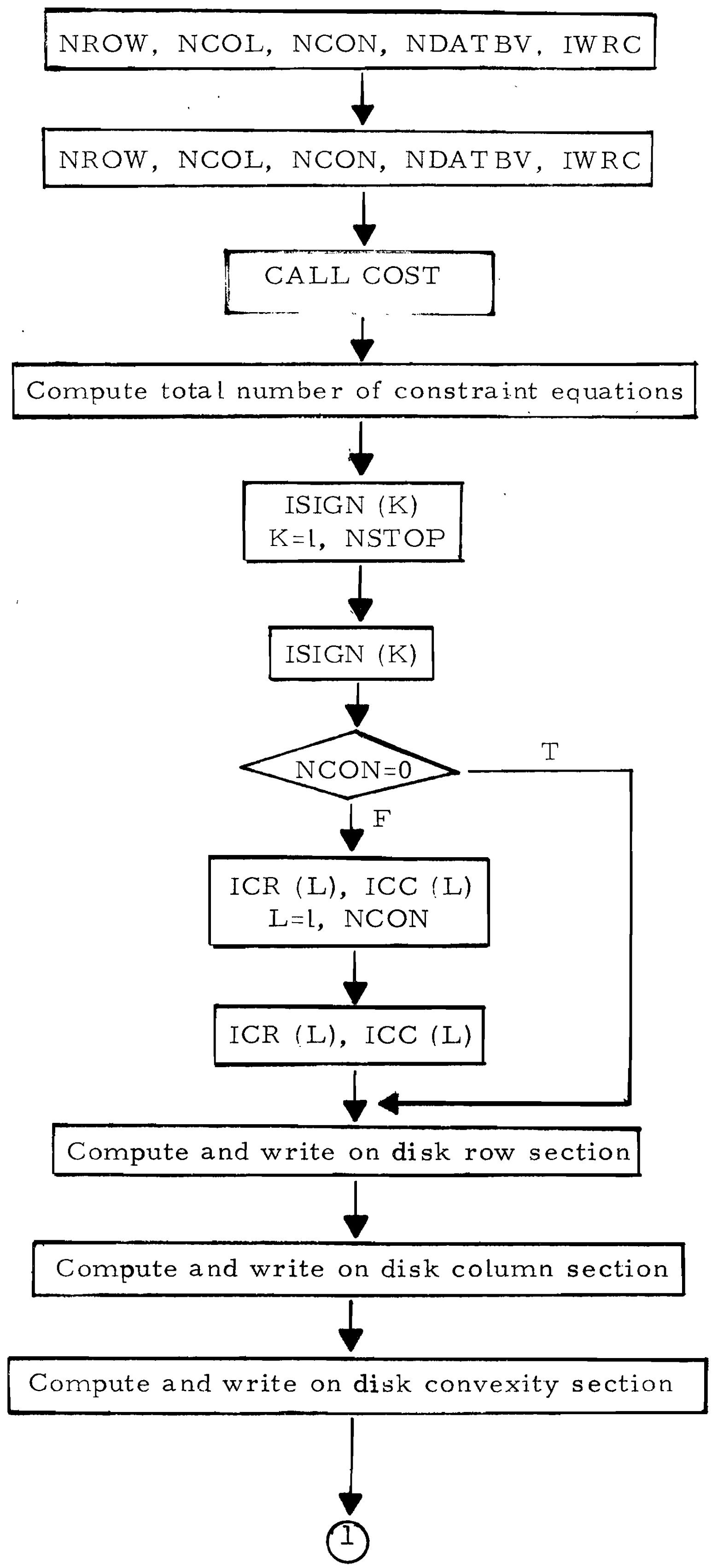
SEP is written in FORTRAN IV for Burrough 6700 at USU computing center. Some necessary modification may be required for any use with other computers. Data file is produced in logical unit 10, which is the diskpack for this facility.

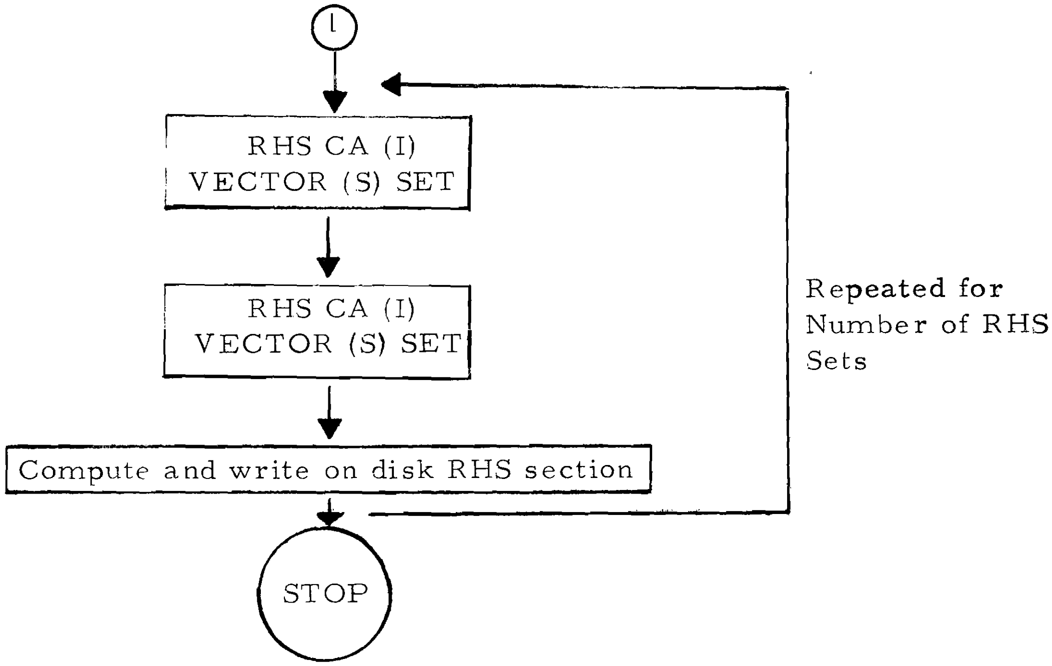
Input data sequence is the transportion matrix characters, number of RHS vector and output option. The number of segments and associated range values to be linearized. The cost functions for any particular use is then read. Exclusion of any undesirable allocation, i.e., allocation is to be zero at all times, is accomplished by assigned the value of BI equal to 9999. Type of constraint equations is read in. Total number of constraint equations is equal to NROW+NCOL+NCON. The RHS vector(s) is then read in set by set. Total number of elements of RHS vector must be equal to number of constraints.

Input Variables Sequence

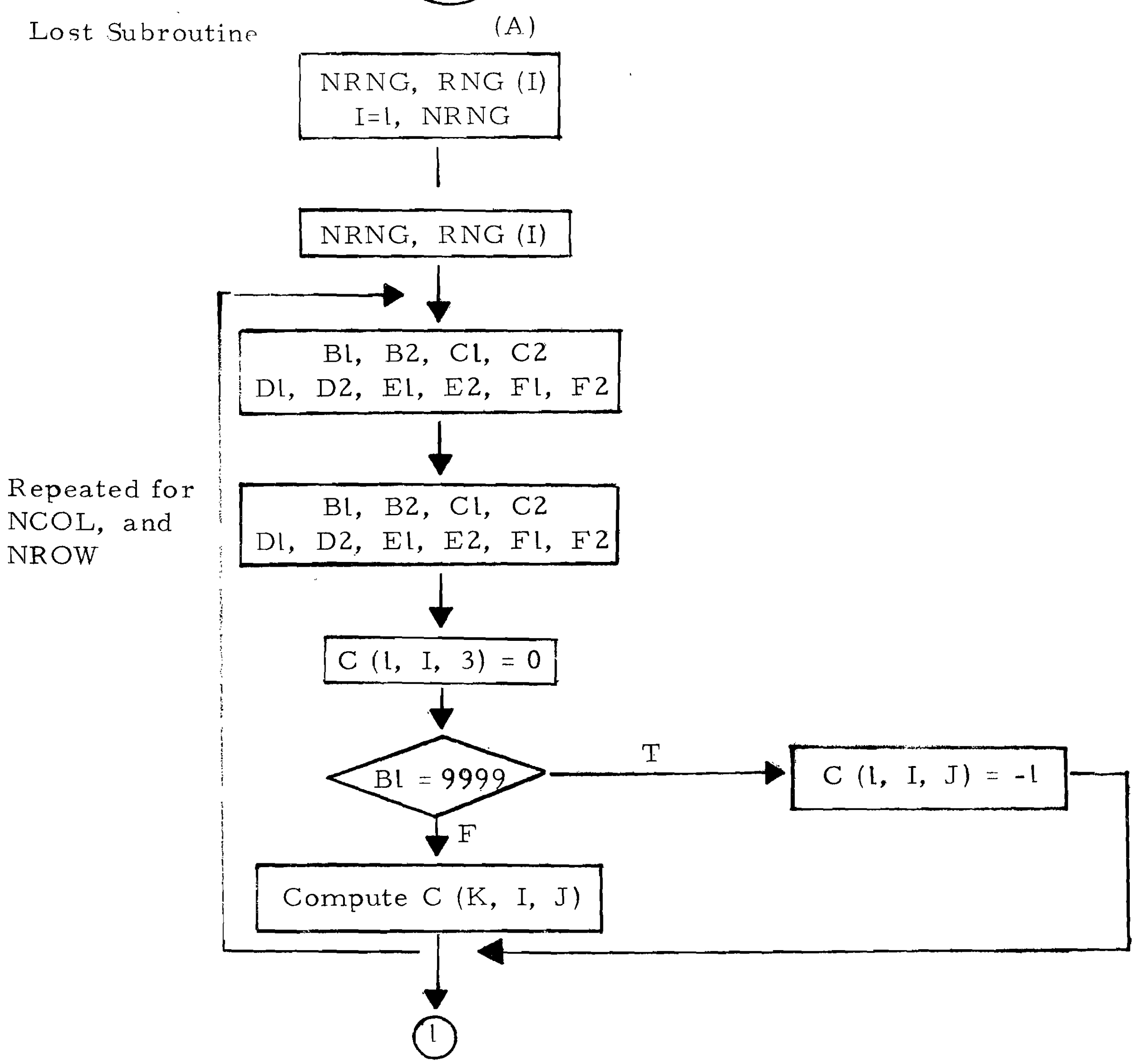
Card Sequence	Field Width	Variable Type	Variable Name
1	5(1-5)	I	NROW
	5(6-10)	I	NCOL
	5(11-15)	I	NCON
	5(16-20)	I	NDATBV
	5(21-25)	I	IWRC
2	1(1)	I	NRNG
	10(6-15)	R	RNG(1)
	10(16-25)	R	RNG(2)
	etc.		
3(1)	8(1-8)	R	B1
	8(9-16)	R	B2
	8(17-24)	R	C1
	8(25-32)	R	C2
	8(33-40)	R	D1
	8(41-48)	R	D2
	8(49-56)	R	E1
	8(57-64)	R	E2
	8(65-72)	R	F1
	8(73-80)	R	F2
	Repeat COST cards of the above format NCOL *NROW cards		
4(1)	1(5)	A	ISIGN(1)
	1(10)	A	ISIGN(2)
	etc.		

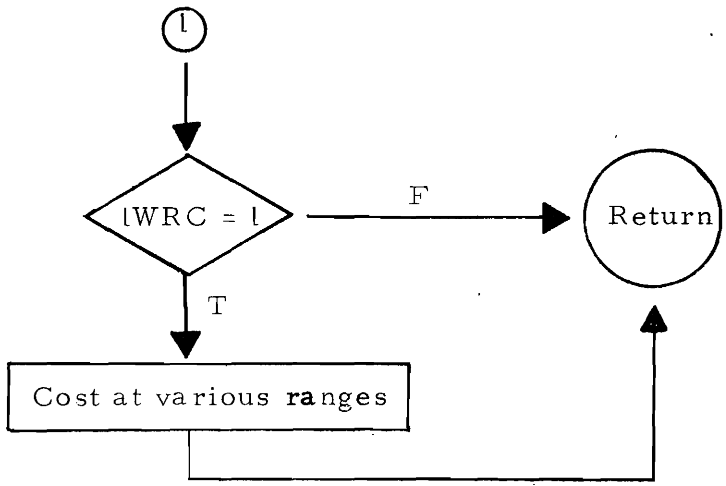
NROW	number of rows of the transportation matrix
NCOL	number of columns
NCON	number of auxillary constraints equations
NDATBV	number of RHS (B vectors)
IWRC	option of printing costs at various range 0 no output 1 output required
B1, C1, D1, E1, F1	coefficient of cost functions
B2, C2, D2, E2, F2	exponent of cost functions
NRNG	number of segments of cost function to be linearized
RNG	range in which each segment is to be linearized
ISIGN	Type of constraints equation E (=) equal to G(⩾) greater than or equal to L(⩽) lesser than or equal to
ICR	row number of auxillary equation
ICC	column number of auxillary equation
IR	logical unit of data file output 10 diskpack on Burroughs 6700 at USU (Line 3 of the program)


NROW, NCOL, NCON, NDATBV, IWRC
NROW, NCOL, NCON, NDATBV, IWRC
CALL COST
Compute total number of constraint equations
ISIGN (K)
K=1, NSTOP
ISIGN (K)
NCON=0
T
F
ICR (L), ICC (L)
L=1, NCON
ICR (L), ICC (L)
Compute and write on disk row section
Compute and write on disk column section
Compute and write on disk convexity section
1



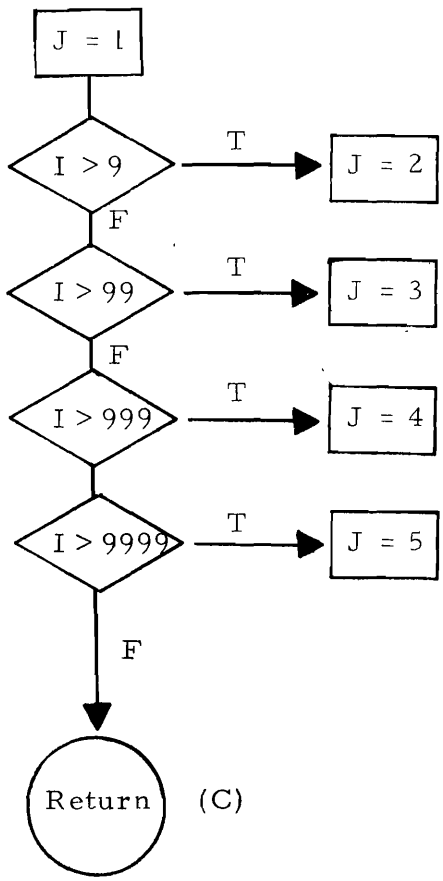
Lost Subroutine





(B)

Subroutine Field



(C)

Figure C-1. A. **Flow Chart of the Main Program**
B. **Flow Chart of the Subroutine Cost**
C. **Flow Chart of the Subroutine Field**

```
FILE    5=GRENNEY/IN
FILE    10=MIDFILE,UNIT=DISKPAC,RECORD=14,BLOCKING=15,AREA=50*1000,SAVE=7
        DIMENSION C(5,50,50),ISIGN(100),VAR(5),ICR(50 ),ICC(50 ),IROW(50)
       *              ,A(50)
        IR=10
        READ(5,50) NROW,NCOL,NCON,NDATBV,IWRC
     50 FORMAT(7I5)
        WRITE(6,51)NROW,NCOL,NCON,NDATBV,IWRC
     51 FORMAT(1H0,6HNROW =,I3,5X,6HNCOL =,I3,5X,6HNCON =,I3,5X
       *          ,8HNDATBV =,I3,5X,6HIWRC =,I2)
        CALL COST(NROW,NCOL,NRNG,C,IWRC,VAR)
        XEND =NROW+NCOL+NCON
        NSTOP= XEND/10.0+0.99
        NEND=XEND
        IADD=NEND-(NSTOP-1)*10
        K1=1
        K2=10
        WRITE(6,53)
     53 FORMAT(1H0 // 1H ,31HV A L U E S   F O R   I S I G N)
        DO 2 I=1,NSTOP
        IF(I.EQ.NSTOP) K2=IADD+K1-1
        READ(5,52) (ISIGN(K),K=K1,K2)
     52 FORMAT(10(4X,A1))
        WRITE(6,54) I,(ISIGN(K),K=K1,K2)
     54 FORMAT(1H0,I4,10(4X,A1))
        K1=K2+1
        K2=K2+10
      2 CONTINUE
        IF(NCON.EQ.0) GO TO 4
        WRITE(6,55)
     55 FORMAT(1H0 // 1H0,22H C O N S T R A I N T S // 1H )
        DO 6 L=1,NCON
        READ(5,56) ICR(L),ICC(L)
     56 FORMAT(2I5)
        WRITE(6,57)ICR(L),ICC(L)
     57 FORMAT(1H ,2I12)
      6 CONTINUE
      4 CONTINUE
        WRITE(IR,61)
     61 FORMAT(    4HNAME,10X,5HREUSE)
        WRITE(IR,63)
     63 FORMAT(    4HROWS)
        WRITE(IR,65)
     65 FORMAT(    1X,7HN   COST)
        DO 1 I=1,NROW
        DO 1 J=1,NCOL
        IF(C(1,I,J).LT.0.0) GO TO 300
        CALL FIELD(I,IFI)
        CALL FIELD(J,IFJ)
        WRITE(IR,58) IFI,I,IFJ,J
     58 FORMAT(1X,6HN   VAR,I*,'A',I*)
    300 CONTINUE
      1 CONTINUE
        NEND=NROW+NCOL+NCON
        DO 3 I=1,NEND
        CALL FIELD(I,IFI)
        WRITE(IR,59) ISIGN(I),IFI,I
     59 FORMAT(1X,A1,2X,3HROW,I*)
      3 CONTINUE
```