METHODOLOGY TO EVALUATE ALTERNATIVE COASTAL ZONE MANAGEMENT POLICIES: APPLICATION IN THE TEXAS COASTAL ZONE*

Special Report II:
A NON-LINEAR PROGRAMMING MODEL FOR EVALUATING WATER SUPPLY POLICIES IN THE TEXAS COASTAL ZONE

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ABSTRACT

The water supply situation in the area of the City of Corpus Christi has the potential of becoming a constraint to development. Available municipal and industrial supplies could be exhausted in the foreseeable future based on reasonable economic growth. A non-linear programming model was developed and used to determine the amount of fresh water required to satisfy future demands and to evaluate the effects of alternate methods for reducing demand on the primary source. In 1974 the use of the available water resource was less than optimal and a 10% reduction in demand was readily available through transfers of water among users. These transfers can represent a 12% reduction in demand by 1990, as a result of the higher quality effluents, required by PL 92-500, The Federal Water Pollution Control Act Amendments of 1972.

The effects of three policies designed to reduce water demand were evaluated. These policies increased the cost of fresh water and the cost of effluent disposal for various combinations of users under the specified conditions. A uniform increase in the cost of fresh water for all users resulted in maximum recycle and reuse of effluents, effecting Zero Discharge of Wastewater. This uniform increase also caused the highest increase in total system cost of all the policies considered. Increasing cost of fresh water for only the industrial sector caused Zero Discharge of industrial wastewater, but the system did not achieve Zero Discharge, since this policy does not provide any economic incentive for the reuse of municipal wastewater. The application of an effluent tax to increase the cost of disposal also resulted in Zero Discharge of industrial return flows, but the reduction in municipal demand was less than with the other two policies. The total demand was reduced about one-third.

The application of these policies would increase the cost of fresh water supply and wastewater treatment considerably, but the total costs still would be about 1 to 2 percent of the gross output of the industrial sector in the area.

High concentrations of Total Dissolved Solids (TDS) in water supply, and thus in the municipal effluents in the area, is the most important constraint to water reuse. Removal of Total Dissolved Solids is required before this water can be recycled, and adds to the cost of the water.

Socio-economic constraints also must be taken into consideration in any decision on water reuse. The methodology developed in this report provides engineering and scientific insights into the effects of different policies of water management.

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CHAPTER 1
INTRODUCTION

GENERAL

The deteriorating quality of the Nation's water resources and the increased demands of municipalities, industries and agriculture on these resources are of current public concern. Water availability at the national level has been given considerable attention and a framework that can be utilized for analysis at this level has been developed. On a nationwide basis, the economic supply - demand situation may be described as follows. The water resource available for development is basically limited to the expected yield from runoff due to rainfall and to the available groundwater. In many water-scarce regions of the United States, maximum development of surface waters is being approached and groundwater utilization is also reaching its limits. Hence, the future supply of water is characterized by increasing costs for the additional quantities of water to be made available. There are a number of technological possibilities for expanding the water resource at a particular area, such as interbasin transfers, but the practicality and economics are uncertain (1), especially during current unstable economic conditions. On the other hand, there are indications that certain toxic materials may be destroying an increasing portion of the existing resource for many uses. A recent example is the discovery of potentially carcinogenic compounds in the Mississippi River at New Orleans, Louisiana (2).

On the demand side, the incremental or marginal values of water of a given quality decrease, sometimes considerably, as the quality of water used increases. This incremental value differs significantly among various users of the resource. The per capita use of water in the municipal sector has continued to increase with income growth. In the past, water-saving technologies designed to offset this increase have not been successful. The total water available can be expected to remain relatively stable or decrease somewhat; therefore, if prices remain at the current low levels, increasing water shortages can be expected at the national, regional, and local levels.

NATURE OF PROBLEM

The primary objective of a preliminary study was the quantitative and qualitative assessment of water requirements of a region and to evaluate the cost to meet various water quality objectives and water requirements. Specific attention was directed at the Coastal Bend Region of the Texas Gulf Coast with emphasis in the Corpus Christi, Texas area. Water use data was collected and analyzed for municipal, industrial, and agricultural consumers. An assessment of the supply and distribution of fresh water was completed and the fresh water resources of the area under drought conditions were quantified. The results of this preliminary evaluation indicated that the water supply situation, especially in the area of the City of Corpus Christi, had the potential of becoming a constraint to development; that is, municipalities, industries, and agricultural users could exhaust reliable supplies in the foreseeable future based on reasonable economic growth and projected population increases.

The modeling approach described in this work was developed in order to investigate management alternatives to minimize this resource constraint. It was felt that the development of such a model had to consider two important points: the non-linearity of cost functions associated with wastewater treatment (economy of scale) and the difference between a "requirement" and a "demand" for water. "Requirement" is the amount of water a user must have for effective operation and "demand" is the actual amount of water withdrawn from fresh water sources. "Demand" should be less than "requirement" because of recycling or inter-industry transfers in cases where the effluent of one user is of suitable quality for the intake of another. The possibility of this inter-industry transfer becomes more likely as the standards for effluents to be imposed in 1977, 1983, and 1985, to meet the water quality objectives of PL 92-500, The Federal Water Pollution Control Act Amendments of 1972, are considered. These standards should cause the treatment of effluents to such quality that the recycle or transfer of effluents would be less costly than purchasing fresh water. In particular, if the 1985 national goal of "no discharge of pollutants into the navigable waters" is achieved, all wastewater will either be recycled, injected into the ground, or evaporated.

OBJECTIVE AND SCOPE OF INVESTIGATION

The objective of this work is the construction of a regional water supply model that considers the difference between "requirements" and "demands" in forecasting future water needs and the non-linearities of the cost functions associated with the treatment of wastewater. This model is applied to the Corpus Christi - Barrier Islands region to determine the amount of fresh water required in the future to satisfy area demands and to determine the effects of alternate policies for reducing demand on the primary source (Nueces River). Alternative policies consistent with proven technological practices and mathematical limitations are evaluated to minimize the demand of present fresh water users and thus provide the maximum potential for economic growth of the region.

The concept of the basin-wide firm introduced by Kneese and Bower (3) is necessary for analysis. This approach assumes the existence of an all-powerful entity or firm that makes all decisions concerning water uses in a basin or region with the objective of minimizing costs for the system as a whole. This approach makes it possible to include all types of industrial and municipal users into the model. Regulatory agencies based on this concept exist in Germany; however, the implementation of such a firm for the Corpus Christi region is not advocated at this time.

This analysis provides an engineering and scientific insight into the effects of different policies of water management. The adoption of any specific practice or policy is not advocated.

CHAPTER 2
REVIEW OF LITERATURE

NATIONAL STUDIES

In 1960, the Senate Select Committee on National Water Resources employed Nathaniel Wolman to forecast water supplies and uses for 22 water resource regions of the Nation (4). The procedure followed by Wolman is summarized below. Major water uses, referred to as requirements, were divided into withdrawal, on-site supply, and flow. Projections for each category were made to the year 2020 based on extensions of contemporary economic trends for each region. Economic supply schedules for water also were developed for each region, based on the costs of development necessary to guarantee different levels of flow. Finally, the least cost combination of flow for wastewater dilution required to maintain a specified level of dissolved oxygen was calculated for each region. The least cost solution was compared with the maximum treatment - minimum flow and maximum flow - minimum treatment options. The analysis indicated that there was a strong possibility of a water shortage in the western regions of the Nation and that the major demand in the East will be for dilution.

In 1965, the United States Geological Survey (USGS) developed projections of water uses and available water resources (5). The USGS study was essentially just a variant of the Wolman study. The same data were used; however, the total water requirements were calculated in a somewhat more liberal way. Greater allowance was made for reservoir losses, and sufficient instream water was allocated to accommodate all instream uses. At the same time, the available water resource was calculated in a more conservative manner; namely, the median rather than the average flow was used.

The Water Resources Council made its first national assessment of the Nation's water resources (6) in 1968, under the Water Resources Planning Act of 1965. Water uses were divided into withdrawals and in-stream. The Nation was divided into 20 water resources regions and 110 sub-regions. Annual water supplies available 50, 90, and 95 percent of the time from natural runoff in each region and sub-region were estimated. Projections of water use were made based on economic trends for each region and regional committees composed of Federal, State and other experts were asked to discuss current and emerging water problems in their regions. This assessment had several weaknesses. The economic demand for water, i.e. quantity as a function of price, was not evaluated; little emphasis was placed on quality; the available flows were estimated without reference to the cost of developing these flows; and probably most important, no analytical system was provided to allow for the examination of alternative assumptions.

Of these three studies, the formulation used by the Senate Select Committee to forecast water use, waste loads, and costs of treatment and storage seems to be most applicable, particularly as revised by Wolman and Bonem in 1971 (7). In contrast to the Council's projection of water quantities only, the Wolman model integrates the hydrologic and economic factors into an analytical framework that can be used for analysis of alternative courses of action. Wolman was able to evaluate the economic cost of supplying increasing quantities of water to maintain a specific water quality.

The primary weakness of the three studies by Wolman, the Council and the USGS was that they all projected the uses of water (withdrawal, consumptive and disposal) as "requirements". Basically, some kind of economic or demographic trend was determined and multiplied by estimated water use coefficients to project requirement. The economic demand of water, i.e. amount withdrawn as a function of price, was not taken into account. The results of a number of other studies (8,9,10) indicate that the quantity of water withdrawn is significantly affected by the price of water. The amount of water used in these water requirement studies was implicitly assumed to be totally independent of price. The fact that the incremental cost of water for various users in different parts of the Nation varies also became obvious. The price of water should rise with increasing scarcity. If the supply is limited, water will be reallocated among the users with the higher incremental or marginal value for the resource, up to the point where the effective price is just covered by the lowest marginal value. This factor was not considered in any of the previous studies, therefore no basis by which policymakers could evaluate the economic effects of present policies and possible modification was provided.

A second difficulty with the three earlier studies was the implicit assumption that policy developments in the future would follow historical trends. Such an approach assumes that all future decisions will be taken according to historical patterns, therefore removing the policymaker from the sequence of events. Obviously, such an approach does not give the policymaker the information required to evaluate the effects of different policies and to make adjustments as necessary. In view of the rapidly changing attitudes towards economic growth and environmental protection that are taking place today, this situation is particularly untenable. New legislation and changing socio-political attitudes will probably significantly affect the previous economic - demographic trends, and these studies cannot be used for a sound and realistic forecast of water use.

Recognizing the problems associated with these previous forecast efforts, in 1970 the Office of Management and Budget requested from the National Water Commission that a refined form of hydrologic analysis be performed in lieu of a second national assessment by the Water Resources Council. Time and resource constraints precluded the development of new models and most of the work was done by contracts to university researchers. The major contract went to Dr. Earl O. Heady at Iowa State University, who evaluated the relative effects of variation in farm and water policies, population growth, export levels, and improvements in technology on the economic demands for water and land in the Nation's agricultural production (11). Heady used linear programming techniques to obtain the least cost use of land and water resources in crop and livestock production, and, in addition, the marginal value of these resources. Conditions for the year 2000 were evaluated under a wide range of population, technology, policy, and foreign trade possibilities. The general indication was that the Nation has developed adequate supplies of land and water resources to satisfy the projected needs of the agricultural sector. These results were in contrast with the results obtained in the other studies discussed previously.

The approach developed by Heady was used by Thompson at the University of Houston in his studies of water needs for industrial use (12). The objective of this work was the development of a comprehensive analytical description of the production and water and wastewater treatment processes of the major water-using industries that could be used to measure scientifically the relative effects of variations in different policies relative to water supply and quality. The industries considered were chemicals, pulp and paper, primary metals, petroleum refining and electric power generation. For each of these categories, the major production activities related to water use were identified and modeled separately. For each type of production modeled, the basic process sequence from raw input to finished product and wastes was delineated. Feasible possibilities for process and input substitutions were considered, together with different wastewater treatment alternatives. The models used were linear and allowed for the development of demand schedules for both the disposal and consumptive uses of water and the determination of marginal values of water used in production. Results were similar to those obtained by Heady, mainly that if enough economic incentive is offered to industrial users in the form of higher costs for fresh water or effluent taxes, the demand will be reduced considerably.

These recent efforts (11,12) were of such a magnitude that linear programming was the only feasible technique for optimization. However, the assumptions of linearity in the cost functions disregards economies of scale, which has been found to be considerable, in particular in the case of wastewater treatment (13,14,15). Consideration of non-linear costs such as those associated with economies of scale would require the minimization of concave functions, which from consideration of computation time is not feasible with problems of the size considered by these researchers. The applicability of these models on a regional basis also is questionable because of the level at which these models were formulated. Assumptions on recycling alternatives and process substitutions that are justified on a national basis are usually unrealistic for a specified region. For example, the industrial models (12) are based on "representative" plants for the major water users. These "representative" plants include the most modern technology available and are of newer design. Such is not the case in an already established industrial zone, which contains a variety of industries of various technologies and different ages.

Two other national models that can be used for rapid, systematic, and comprehensive assessment of the impact of major pollution control programs upon the environment and the economy are SEAS (Strategic Environmental Assessment System) and MERES (Matrix of Environmental Residuals from Energy Systems) (16). SEAS was developed by the Environmental Protection Agency (EPA) and became operational in 1974 in prototype form. It is a system of special purpose models linked to an input-output model of the United States economy which models the interactions between 185 different economic sectors and is used to project the generation of environmental residuals. MERES is not a model, but a computerized data base permitting rapid and comprehensive analysis of the direct environmental effects of energy supply and use. MERES cannot be used for projecting levels of energy consumption, but does compute in detail the implications of alternate energy consumption scenarios supplied in terms of energy efficiency, costs, air pollution, water pollution, solid waste generation, land use, and occupational health and safety.

These tools are in the formative and development stage and are undergoing testing, expansion, verification, and documentation. However, some results already have been produced and the further development should assist decisionmakers in assessing policies.

REGIONAL STUDIES

The various techniques of operations research have been used extensively in the water resources field since the initial work of Pavelis and Timmons on watershed planning (17). This work involved a linear model of the Nepper Watershed and showed that watershed planning can proceed on a basis in which measures are combined in such a way as to render aggregate net benefits a maximum, but subject to stated constraints imposed by the availability of natural resources. Other linear programming formulations were those by Sobel (18) and more recently by Andrews and Weyrick (19). Sobel outlined the nature of regional water quality systems and presented programming models for several water quality improvement problems. Andrews and Weyrick formulated a linear programming model for a river basin that would include almost all water-related economic activity for consumers and producers. On the wastewater treatment sector, results showed that the cost to industry was less when effluents were discharged to municipal treatment systems than when industry treated the effluent. The timely scheduling, construction, and expansion of water resource projects has been considered by Haimes and Nainis (20). A dynamic programming algorithm is used to solve a planning model which provides a least cost schedule for the development of projects. This methodology allows multiple projects to be scheduled over a given time horizon.

The problem of river basin planning for water quality also has received wide attention. The objective is the determination of how the stream dissolved oxygen standards can be met in the most efficient way. Since funds are usually limited and a considerable combination of removal efficiencies that will provide satisfactory stream water quality levels are available, the question becomes one of economics. The goal is to select the efficiencies that will achieve the dissolved oxygen standards at minimum cost. Mathematical programming has been utilized to explore this question in a number of studies by Deininger (21), Kerri (22), Liebman (23), and Revelle et al. (24,25). These models used the oxygen sag equation formulation of Streeter and Phelps (26), Dobbins (27) or Camp (28) to either allocate the required treatment efficiencies among the various polluters or to maximize the obtainable standard with the funds available. Linear programming is the optimization tool used, except by Liebman (23), who used dynamic programming on the Willamette River to minimize the cost of providing waste treatment to meet a specified dissolved oxygen concentration standard. Further work, again using linear programming, was reported by Revelle, Dietrich and Stensel (29).

As in the case of national models, the main advantage of using linear programming in regional models is the ease of solution, since a considerable number of algorithms are readily available. Post-optimality analysis also is relatively easy, and probably more important, the marginal prices of water for the different users are obtained. The main disadvantage is that real world cost functions are usually non-linear, as discussed previously. Linear constraints are realistic in many cases, particularly when mass balances are involved. However, in the case of cost functions for waste-water treatment, equations are usually power functions. This problem can be solved. One possibility is to use integer programming, as done by Salcedo and Weiss (30). The best approach involves the use of non-linear programming, and some work in this direction was reported by Guise and Flinn (31) and Deininger (32). The problem with non-linear programming algorithms is that the amount of computer time involved can be considerable. Another drawback is the difficulty encountered in obtaining confidence intervals on the results. However, if the region under consideration is small, the computer time constraint almost can be eliminated, and then the non-linearity of the objective function provides a better representation of the actual situation. Such is the case with the region to be considered in the study presented herein.

CHAPTER 3
THE MATHEMATICAL MODEL

THE MATHEMATICAL STRUCTURE

A set of water users in a region is established and the variables defined as:

S_i	ith user, up to n
D_i	water requirement of S_i
Q_i	fresh water intake at S_i (demand)
x_{ij}	amount of water that S_i receives from S_j
x_{ii}	amount of water recycled by S_i
C_{ij}	unit cost of sending water from S_j to S_i
T_{ij}	unit cost of treating water from S_j so that it meets input quality requirements of S_i
L_i	water loss at S_i
Z_i	volume of wastewater in the effluent of S_i
R_i	unit cost for wastewater disposal at S_i
K_i	unit cost of fresh water at S_i
P_i	effluent tax

The total amount of fresh water available is represented as S_o, and S_w is the sink for all wastewater. The above system is represented as shown in Figure 3.1.

For an optimal utilization of the available amount of water, the objective is:

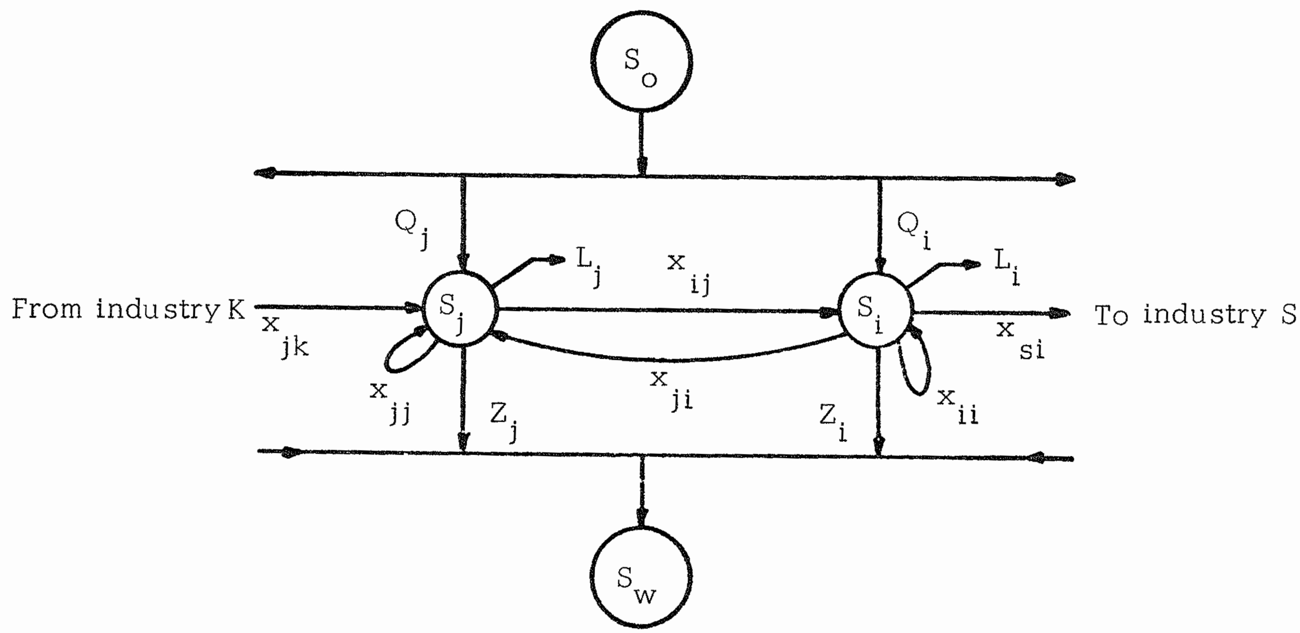


FIGURE 3.1
MODEL STRUCTURE

$$\text{minimize } f = \sum_{i=1}^{n} \sum_{j=1}^{n} (C_{ij}+T_{ij})\, x_{ij} + \sum_{i=1}^{n} K_i Q_i + \sum_{i=1}^{n} (P_i+R_i) Z_i \tag{3.1}$$

subject to:

$$\begin{aligned}
\sum_{i=1}^{n} x_{1i} + Q_1 &= D_1 \\
\sum_{i=1}^{n} x_{2i} + Q_2 &= D_2 \\
&\vdots \\
\sum_{i=1}^{n} x_{ni} + Q_n &= D_n
\end{aligned} \tag{3.2}$$

$$\begin{aligned}
Q_1 - L_1 - \sum_{j=2}^{n} x_{j1} + \sum_{j=2}^{n} x_{1j} - Z_1 &= 0 \\
Q_2 - L_2 - \sum_{\substack{j=1 \\ j\neq 2}}^{n} x_{j2} + \sum_{\substack{j=1 \\ j\neq 2}}^{n} x_{2j} - Z_2 &= 0 \\
&\vdots \\
Q_n - L_n - \sum_{j=1}^{n-1} x_{jn} + \sum_{j=1}^{n-1} x_{nj} - Z_n &= 0
\end{aligned} \tag{3.3}$$

$$\sum_{i=1}^{n} Q_i \leq S_o \tag{3.4}$$

$$x_{ij} \geq 0 \quad \forall i,j$$

$$Q_i \geq 0 \quad \forall i \qquad (3.5)$$

$$Z_i \geq 0 \quad \forall i$$

The constraints given by Equation 3.2 indicate that the water "requirement" of each user must be satisfied, either with fresh water, recycled water, or water from the effluent of another industry. Equation 3.3 defines the mass balances for each user in terms of the decision variables and Equation 3.4 establishes an upper limit on the total amount of water available. The non-negativity constraints are given by Equation 3.5.

Only one fresh water source, a surface reservoir, is assumed. If fresh water also is available from ground water or from a desalination plant, additional terms can be added to the equations.

The 1985 national goal of no discharge of pollutants into the navigable waters is assumed to mean no discharge of wastewater. An estimate of the economic implications of this policy can be obtained by letting $Z_i = 0$ in the model.

A variety of alternatives for wastewater discharge also is possible; however, discharge to a surface body of water will be the only alternative considered. Other schemes such as deep well injection and some type of irrigation easily can be added.

MATHEMATICAL CONSIDERATIONS

The water requirement (D_i) and the water loss (L_i) of a user are relatively easy to obtain and do not create any mathematical difficulty. The effluent tax P_i depends on definition. A possible approach is imposition of a charge on the mass of a specified pollutant, usually BOD or suspended solids, to be discharged. These values would be in the range of a few cents per pound of pollutant, similar to the surcharges used by some municipalities that treat industrial wastewaters (33) (34). Such a tax would encourage users to treat the effluent and once high quality is achieved, recycle or inter-industry transfers would occur. The difficulty in the analysis of this type of tax is mathematical. The tax cannot be incorporated into the objective function or the creation of a constraint that would account for the different removal efficiencies of the various processes for the individual pollutants in wastewater treatment also is not possible. A second consideration is the imposition of the effluent tax in the form of cents/1000 gallons of effluent discharged, independent of quality. This tax would be similar to the surcharge imposed by Kansas City, Kansas on the treatment of industrial wastewaters. This tax would encourage recycling or reuse at that point where the cost to install a treatment scheme to clean and reuse the water is less than the cost of discharging the effluent. The advantage from the enforcement point of view lies in the simplicity of this approach. A simple instrument to measure cumulative flow over a given period of time is the only requirement. The mathematical advantage is that P_i can be expressed as a simple constant for each user. Therefore, this form of tax is considered in this model.

The cost of fresh water, K_i, is a step function when plotted as unit cost versus volume of water consumed. Such a plot for the pricing structure in effect at the Corpus Christi area during the base year, 1974, is presented in Figure 3.2. The first few gallons of water used have a relatively high unit price, but as the consumption increases, the unit cost decreases. However, this decrease in unit cost occurs over very wide ranges, and once a certain amount of water has been used, the unit cost remains constant. Therefore, for a given user, with a specified amount of water use every month, the cost K_i can reasonably be assumed as a constant.

The unit costs of transmission (C_{ij}), of water treatment (T_{ij}), and of waste treatment (R_i) are functions of the form ax^b, where $-1 \leq b < 0$ for all cases. These functions are all multiplied by x, and take the form $a^*x^{b^*}$, where now $0 \leq b^* < 1$. Taking derivatives of these functions results in the following expressions:

$$f'(x) = a^*b^*x^{(b^*-1)} \qquad (3.6)$$

$$f''(x) = a^*b^*(b^*-1)\, x^{(b^*-2)} \qquad (3.7)$$

Since x is a non-negative number, the second derivative is always negative, which means that the function is concave. The sum of concave functions is concave, making the objective function of the model a concave function to be minimized.

In more formal mathematical terms, the convexity or concavity of a function assist in determining under what conditions a local optimal solution also is the global optimal solution. If the function f(X) is to be minimized over E^n subject to a number of constraints, a global optimal solution f(X*) at X* represents the smallest value of f(X). A local or relative optimal solution represents the smallest

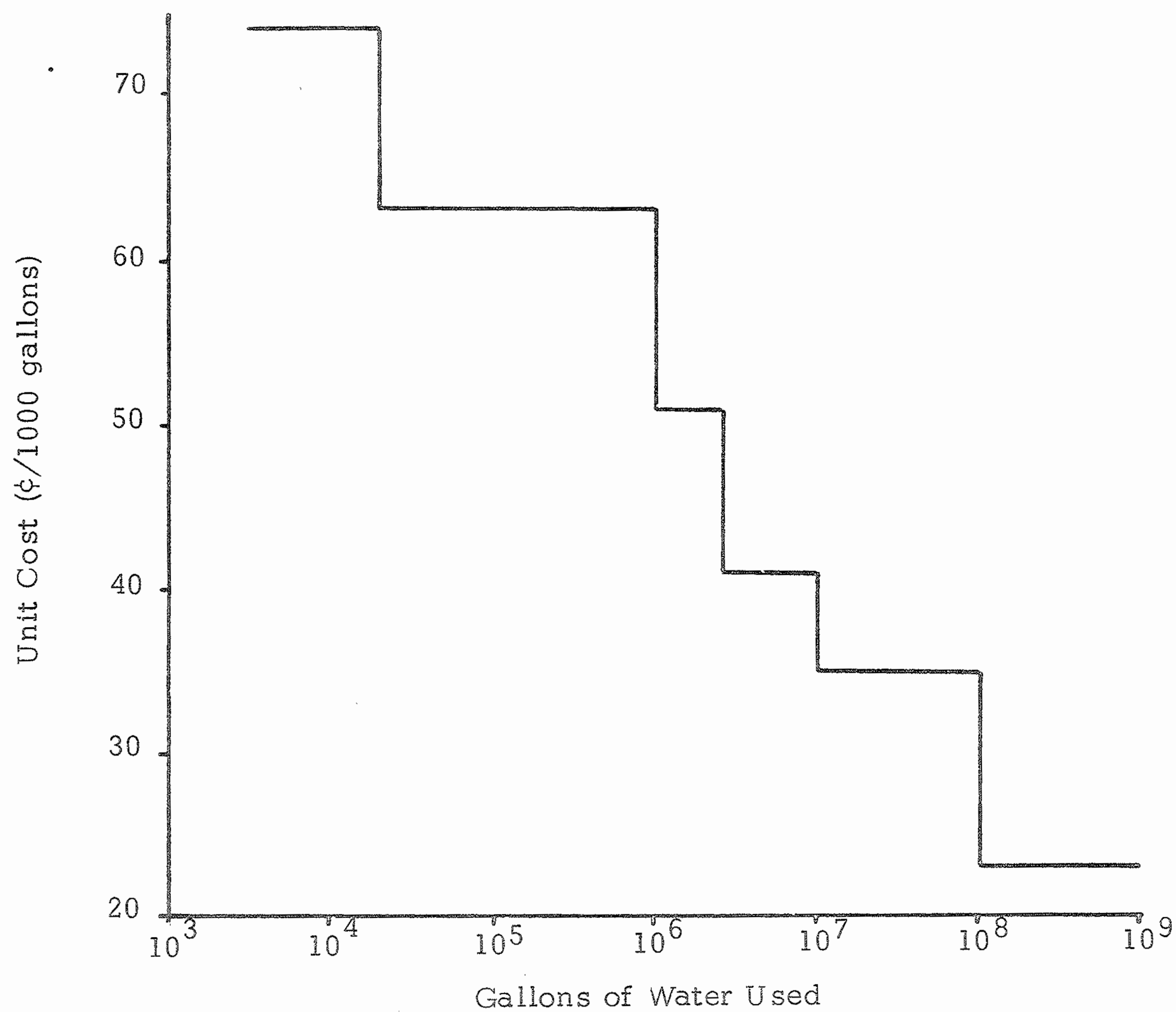


FIGURE 3.2
UNIT COST OF WATER

value of f(X) in the vicinity of some x vector. The value of the objective function at the global minimum is less than or equal to the value at any local minimum, but the global optimal solution refers to all $X \epsilon E^n$, while the local optimal solution refers to a small region δ, such that $|X - X^*| < \delta$.

Considering the general non-linear programming problem:

$$\text{minimize} \quad f(X) \quad X \epsilon E^n$$

$$\text{subject to} \quad h_i(X) = 0 \qquad i = 1, \ldots m \qquad (3.8)$$

$$g_i(X) \geq 0 \qquad i = m+1, \ldots p$$

The conditions under which convergence to the global optimal solution of problem (3.8) is guaranteed was described by Himmelblau (35) as:

a. $f(X)$, $h_i(X)$ and $g_i(X)$ are all continuous and differentiable functions
b. $g_i(X)$ is concave for all i
c. The domain of X for which $g_i(X)$ and $h_i(X)$ are satisfied, R, must be closed and convex
d. The constraint functions are bounded
e. The feasible region is not empty, that is, there is at least one X which satisfies the constraints
f. $f(X)$ is convex

Since the constraints in the proposed model are all linear functions, $h_i(X)$ and $g_i(X)$ are continuous, differentiable, bounded and both convex and concave. R is also closed and convex and hopefully there will be at least one feasible point to satisfy condition e. The difficulty lies in the objective function, which is not only concave, but also discontinuous and not differentiable at the origin. Therefore, the majority of non-linear programming algorithms, such as those given by Himmelblau (35), cannot guarantee convergence to the global minimum and the application of some type of search algorithm is required.

MATHEMATICAL ALGORITHM FOR NON-LINEAR PROGRAM

The method proposed by Cabot and Francis (36) and extended and generalized by Deininger and Su (37) was used. Generally, the method proceeds as follows:

Let problem P_1 be:

$$\text{minimize } f(X) = \sum_{i=1}^{n} f_i(x_i) \tag{3.9}$$

$$\text{subject to} \quad AX = v \tag{3.10}$$

$$0 \le X \le B$$

with A a given matrix of order m x n, v a given vector of order n x 1, and X a vector of variables of order n x 1. All of the $f_i(x_i)$ in P_1 are of the form $a_i x_i^{b_i}$ where $0 \le b < 1$ and a_i and b_i are given constants.

Each of the $f_i(x_i)$ can be rewritten in the form

$$f_i(x_i) = \frac{a_i}{x_i^{1-b_i}} x_i \tag{3.11}$$

and let $$U_i = \min_{x_i} \frac{a_i}{1-b_i} \tag{3.12}$$

Therefore, a related linear program (P_2) can be written:

P_2:

$$\text{minimize } g(X) = \sum_{i=1}^{n} U_i x_i \tag{3.13}$$

$$\text{subject to} \quad AX = v \tag{3.14}$$

$$X \geq 0$$

Since all the x_i are bounded, U_i can be obtained as:

$$U_i = \frac{a_i}{1-b_i}\Big|_{B_i} \tag{3.15}$$

It can be shown that if W is the set of feasible solutions to P_1, then:

1. For any $X \in W$, $g(X) \leq f(X)$
2. If X^0 is an optimal solution to P_2, then $f_l = g(X^0)$ is a lower bound on the optimal value of P_1, f^*, and $f_u = f(X^0)$ is an upper bound
3. Given any f_u on f^*, denote by $\{X^k\}$ the set of all extreme points of P_2 such that $g(X^k) \leq f_u$, then P_1 has an optimal solution X^* such that $X^* \in \{X^k\}$

The algorithm begins by solving P_2 to obtain an initial feasible solution to P_1 and the procedure for ranking the extreme points developed by Murty (38) and described later generates new upper and lower bounds until both bounds converge at the optimum of P_1.

The algorithm developed by Cabot and Francis (36) proceeds as follows:

1. Solve P_2 to obtain an optimal solution X^0; take $f_l = g(X^0)$ as a lower bound on f^*
2. Take $f_u = f(X^0)$ as an upper bound on f^*, take X^0 as the "current best solution" to P_1
3. A "next best" extreme point solution X^k to P_2 is determined by using Murty's extreme-point ranking procedure. If $g(X^k) > f_u$, then stop. The "current best solution" is a minimum solution to P_1, and $f^* = f_u$. If $g(X^k) \le f_u$, then replace f_l by $g(X^k)$; f_l is a lower bound on f^*
4. If $f(X^k) < f_u$ replace f_u by $f(X^k)$ and replace the "current best solution" to P_1 by X^k; f_u is an upper bound on f^*. Otherwise, return to step 3 without changing f_u or the "current best solution"

This algorithm was modified slightly in the way in which the initial upper bound f_u was obtained. The functions $a_i x_i^{b_i}$ were linearized to $a_i x_i$ and the resulting linear program was solved to obtain an X solution vector. The initial upper limit f_u was then taken as $f(X)$ and X as the "current best solution". This modification provided a more efficient way, in terms of computer time, to reach the optimal.

Once the procedure described above stops, the global minimum is obtained. The difficulty is that there is no way to predict beforehand how many points will have to be ranked before the solution is obtained. Deininger reported that the worst case amounted to about

40 percent of the possible extreme points and the author's experience indicates about 20 percent.

MURTY'S EXTREME-POINT RANKING METHOD (38)

The standard form of the linear programming problem may be expressed as:

$$\text{minimize } f(X) = cX \tag{3.16}$$

$$\text{subject to} \quad AX = b, \quad X \geq 0 \tag{3.17}$$

If the problem has a finite optimal solution, it is well known that there exists a vertex of Equation (3.17) that is optimal for the above problem. The algorithm described here is an extension of the simplex algorithm which uses one step pivot operations to rank the basic feasible solutions of a linear program in order of increasing f once the optimal is obtained by the simplex method. This approach was developed by Murty as a method by which to obtain the minimal cost solution to the fixed charge problem.

Basically, the method includes:

> The letters B and E are set with the appropriate subscripts or superscripts, which denote the basic feasible solutions of the linear program. Let $x_1, x_2 \ldots x_m$ be the basic variables associated with the base B. The expression becomes:

$$x_i \in B \text{ and } B = \{x_1, \ldots x_m\} \tag{3.18}$$

Assuming that the problem has a solution, let W_1 denote the minimal cost basic feasible solution and W_{max} the maximal cost basic feasible solution. For any basic feasible solution B and corresponding to any non-basic variable $x_j \notin B$, let:

C_j^B = the relative cost coefficient of the non-basic variable x_j corresponding to the basis B

Θ_j^B = the value with which the non-basic variable x_j enters the basis in the canonical form of the linear program with B as a basis

E_j^B = the new basic feasible solution obtained by pivoting on the column of x_j in the canonical form of the linear program with B as a basis.

From the simplex algorithm,

$$f(E_j^B) = f(B) + \Theta_j^B \; C_j^B \tag{3.19}$$

The basic solutions E_j^B for j such that $x_j \notin B$ are adjacent vertices of the vertex B. The canonical form corresponding to any of the adjacent vertices of B can be obtained by pivot operations on the canonical form of B. Therefore, by successive pivot operations, each vertex of the polyhedron can be reached.

The ranking of the vertices proceeds as follows:

Let W_1, W_2 ... be a ranking of the basic feasible solutions of the linear program in order of increasing f. W_1 is obtained from the optimal solution to the linear program, evaluated with the simplex algorithm. From the proof of the simplex algorithm, it is known that there exists a cost non-increasing path moving along adjacent vertices from the initial basic solution B to W_1. By taking the same path in the reverse direction from W_1, B can be reached from W_1 by moving along adjacent vertices along a cost non-decreasing path. It is then obvious that the next element in the sequence $W_1, W_2 \ldots W_{k-1}$ must be a cost non-decreasing adjacent vertex of one of the vertices represented by the known basic feasible solutions $W_1, \ldots W_{k-1}$. Therefore, once the sequence up to W_{k-1} is known, the next element W_k can be obtained by examining the values $f(E_j^B)$ for $i = 1, 2 \ldots k-1$ and j such that $x_j \not\in W_i$ and $C_j^{w_i} \geq 0$. W_k is that new basic feasible solution that is distinct from $W_1, \ldots W_{k-1}$ and that has least cost value $\geq f(W_{k-1})$. The values of each $f(E_j^B)$ are obtained from Equation (3.19).

This algorithm is step-wise and in each step an additional element in the sequence of ranked vertices is obtained. Computationally, Murty suggests the use of three arrays for storage of the following:

Array I: All the $f(E_j^{w_i})$ values for each W_i determined so far, for all j such that $x_j \not\in W_i$ and $C_j^{w_i} \geq 0$ and $E_j^{w_i}$ is different from any of the W_i evaluated so far.

Array II: All the basic feasible solutions that have already been found and ranked, i.e., $W_1, W_2, \ldots W_{k-1}$.

Array III: The basic feasible solutions $E_j^{w_i}$ corresponding to the f values stored in Array I.

The size of the arrays indicate the convenience of storing Array I and Array II in core memory and Array III on tape.

Once W_{k-1} has been obtained, the computations required to obtain W_k are:

a. Scan Array I completely and determine the least value there.
b. Identify and retrieve the corresponding basic solution from Array III. This is W_k. To obtain more elements in the sequence:
c. Remove $f(W_k)$ from Array I, W_k from Array III, and add W_k to Array II.
d. Find the canonical form of W_k and using Equation (3.19) obtain all of its cost non-decreasing adjacent vertices. Store the basic feasible solutions in Array III and their respective f's in Array I.

When this method is used in conjunction with the Cabot and Francis algorithm (36) discussed previously, Array II is not necessary since as the elements in the sequence are obtained, they are compared to the previously evaluated upper and lower bounds and only the "current best solution" is stored.

LINEAR PROGRAMMING ALGORITHM

The application of the non-linear programming algorithm requires that the linear programming algorithm be accessed as a subroutine. The subroutine used was developed by Clasen (39).

The procedure used for solution is the simplex method using the "explicit inverse" variation. Using variable names from the subroutine, it proceeds as follows:

a. Determine an initial basis. If a basis is already available, check the solution vector for feasibility. Let the basic part of the solution vector be $B = \{x_1, x_2 \ldots x_m\}$.
b. Evaluate the "phase one" prices if the problem is not yet feasible, the "phase two" prices if the problem is feasible.
c. Calculate the reduced costs and find the column, JT, with the minimum reduced cost, MRC. If MRC < 0, JT is the pivot column. Otherwise, an optimal solution has been reached and the subroutine terminates.
d. Obtain the column vector JT by multiplying the inverse and the original column JT. Rename this column as Y, with elements $y_1, y_2 \ldots y_m$.
e. Find the pivot row, IR, by using the i that minimizes x_i/y_i for all non-zero y_i for which $x_i/y_i \geq 0$. If no row is found, the solution is infinite, an error message is generated, and the subroutine is terminated.
f. Update the inverse, the "phase two" prices, and the x_i by executing a pivot operation on (IR, JT).

These steps are repeated until an optimal solution is reached in Step c, an infinite solution in Step e, or the number of iterations exceeds a specified limit. The initial bases may be vacuous and the initial inverse may be the identity. An additional feature of the subroutine is the re-inversion of the basis every m/2 to m iterations. This helps to decrease the round-off error. In order to invert every NVER times, a counter (INVC) is used together with the following step:

g. Increase counter by one. If INVC < NVER, go to Step a. Otherwise, set INVC to zero and invert the basis, then go to Step a.

The subroutine as given by Clasen was modified slightly by using common storage to reduce the required core memory.

CHAPTER 4
RESULTS

DESCRIPTION OF AREA

The model described previously was applied to the Corpus Christi - Barrier Islands region of the Texas Coastal Zone. This area contains thirteen industrial and thirteen municipal water users and is shown in Figure 4.1. The water supply for the area is obtained from the Nueces River and its tributaries. Surface impoundment is necessary since the natural flow of the river varies from no flow during the dry season to as much as 141,000 cubic feet per second during flood periods (40). Impoundment is accomplished through the use of the Wesley Seale Dam and the 304,000 acre-feet Lake Corpus Christi, located about 35 miles upstream from the City. The safe yield of this reservoir is estimated at 121 MGD in 1975, but there is some question as to the future availability of this amount. Storm flood from Hurricane Beulah in 1967 caused heavy silting which reduced the capacity and dependable yield of the Lake. Runoff is a continuous source of silt and hurricanes pose a continuous threat. Industrial development is contingent on the availability of water, therefore the City of Corpus Christi has taken steps to increase the available amount of water. A field survey conducted by the Bureau of Reclamation recommended a 700,000 acre-feet site at Choke Canyon on the Frio River upstream from Lake Corpus Christi and the City of Three Rivers. The estimated combined yield of this reservoir and the existing Wesley Seale Dam will be 225 MGD.

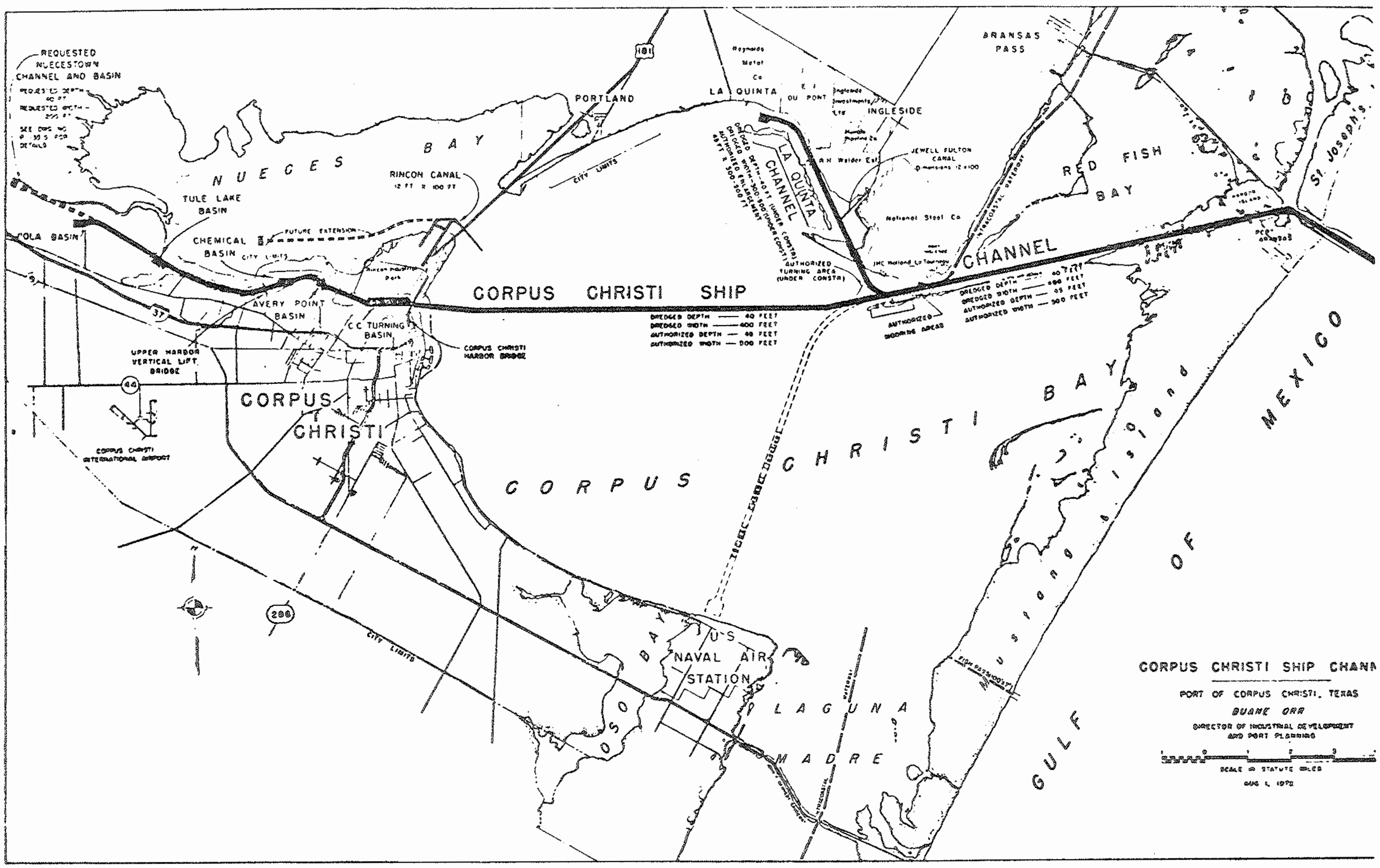


FIGURE 4.1

AREA OF INTEREST

The total available average flow in the Lower Nueces River will support one additional reservoir. A field survey conducted by the engineering firm of Reagan and McCaughan suggested a site some five miles from the City limits which could provide more water than the Choke Canyon Reservoir. In 1970 the voters of Corpus Christi selected the Reagan and McCaughan site and the City Council requested that the Bureau of Reclamation obtain authorization from Congress for the construction of such reservoir. No action has been taken to date on the construction of either reservoir.

Instead of trying to increase the available water in the area, the possibility of reducing demand on the primary source should be considered. One approach to reduce the demand on the water resources of Lake Corpus Christi is to encourage recycling and transfers of water among users. The existence of a basin-wide firm will result in reduction of the demand when the price of fresh water and the cost of effluent disposal exceed the cost of recycled water. This firm would increase costs of fresh water to encourage recycling. Possible combinations of policies are myriad, therefore those alternatives that seem more likely will be evaluated.

DESCRIPTION OF DATA FOR BASE CASE

The use of the model required quantification of the water that can be transferred, identification of potential users, and the costs. Natural and distance constraints divide the region into four groups, as shown in Figure 4.2. Each of these groups is considered individually.

The cost for transferring water from one user to another includes two parts, namely the cost of conveyance and the cost of

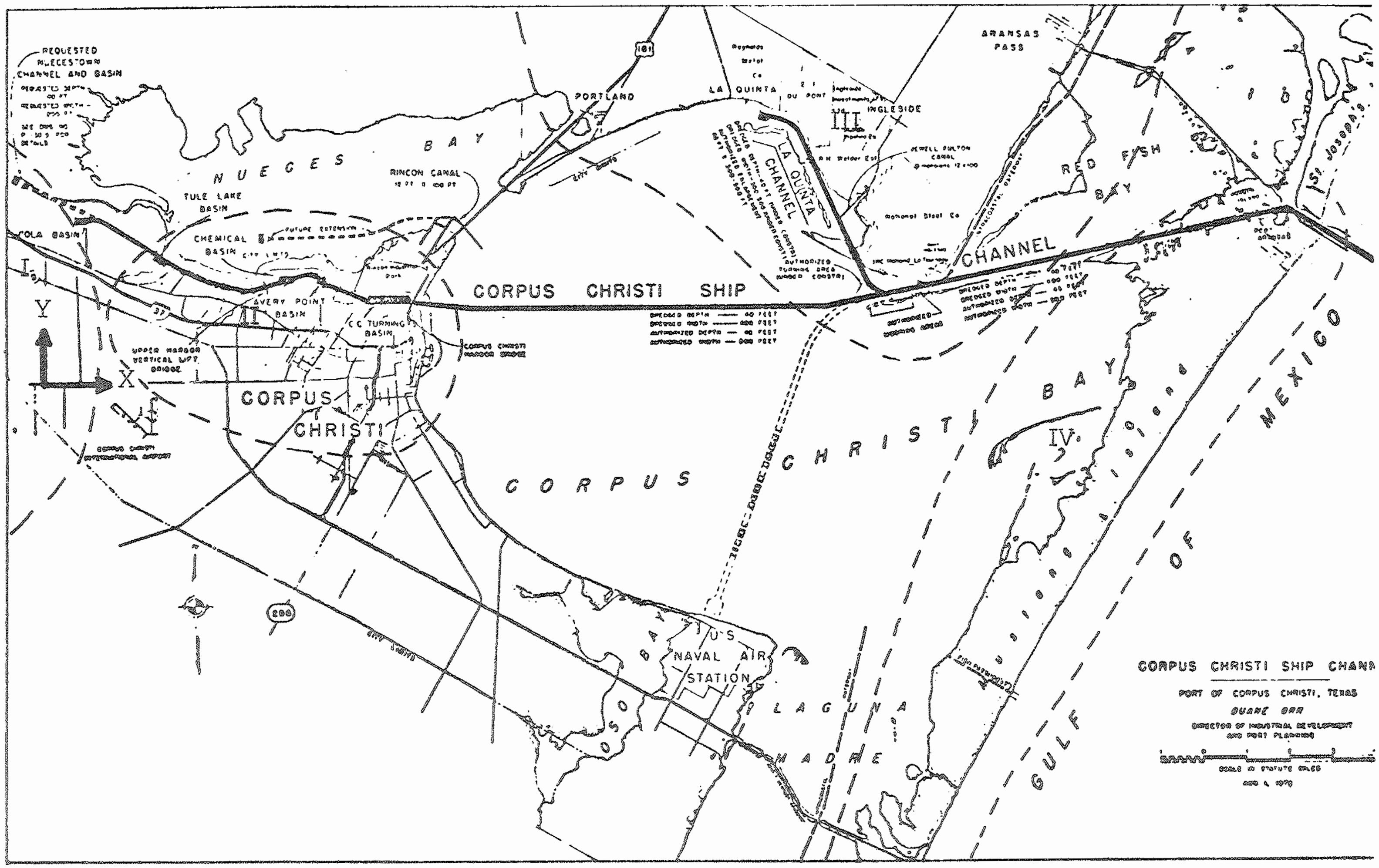


FIGURE 4.2
DIVISIONS OF AREA OF INTEREST

treatment necessary to produce a water of acceptable quality to the user. The following equation developed by McConagha and Converse (41) can be used to estimate the cost of conveyance.

$$\text{cost}\ \left(\frac{\text{¢}/1000\ \text{gal}}{\text{mile}}\right) = 1.25\ (\text{flow})^{-0.505} \qquad (4.1)$$

where flow is in MGD.

The geographical locations of users with respect to an arbitrary center of coordinates shown in Figure 4.2 are summarized in Table 4.1. The distance between users is calculated and those possibilities which exceed a specified limit are rejected. This distance is also used with Equation 4.1 to obtain the cost of conveyance in cents/ 1000 gal.

The cost of treatment is dependent on the treatment sequence required to produce a product of acceptable quality for reuse or discharge into the receiving waters. The treatment system selected to produce water of drinking water quality from almost any intake wastewater is presented in Figure 4.3. The cost equations for each of the individual processes are shown in Table 4.2, while the removal efficiencies for BOD, SS, and TDS are summarized in Table 4.3. Cost equations as given in Table 4.2 are updated to correspond to an Engineering - News Record Construction Cost Index value of 1942, which corresponds to April 1974. The Index value used in the actual evaluation of the different cases considered was 2021, which is the average value for the year 1974. Since the percent removals required for the different interindustry transfers vary, only that part of the treatment system required to achieve the necessary water quality levels was considered.

Center of Coordinates is located at intersection of Rand - Morgan Road and Tex - Mex Railroad.

User	X-Coordinate (miles)	Y-Coordinate (miles)	Group
Industry 1	1.4	3.5	II
Industry 2	4.0	2.2	II
Industry 3	5.0	1.9	II
Industry 4	5.4	1.8	II
Industry 5	5.9	1.8	II
Industry 6	6.7	1.6	II
Industry 7	7.0	2.0	II
Industry 8	7.4	1.7	II
Industry 9	7.6	1.4	II
Industry 10	7.9	2.3	II
Industry 11	16.6	6.6	III
Industry 12	17.8	7.4	III
Industry 13	-16.9	-14.3	I
Corpus Christi	6.5	- 1.1	II
Robstown	6.8	5.6	I
Alice	-31.2	- 2.5	I
Odem	- 2.3	10.7	III
Taft	9.0	12.9	III
Gregory	15.2	9.0	III
Portland	13.2	5.9	III
Aransas Pass	23.9	7.9	III
Port Aransas	29.0	2.8	IV
Ingleside	20.0	5.9	III
Mustang Island	23.8	- 3.8	IV
Padre Island	21.0	-10.7	IV
Nueces Park	21.0	-10.8	IV

TABLE 4.1
GEOGRAPHICAL LOCATION OF USERS

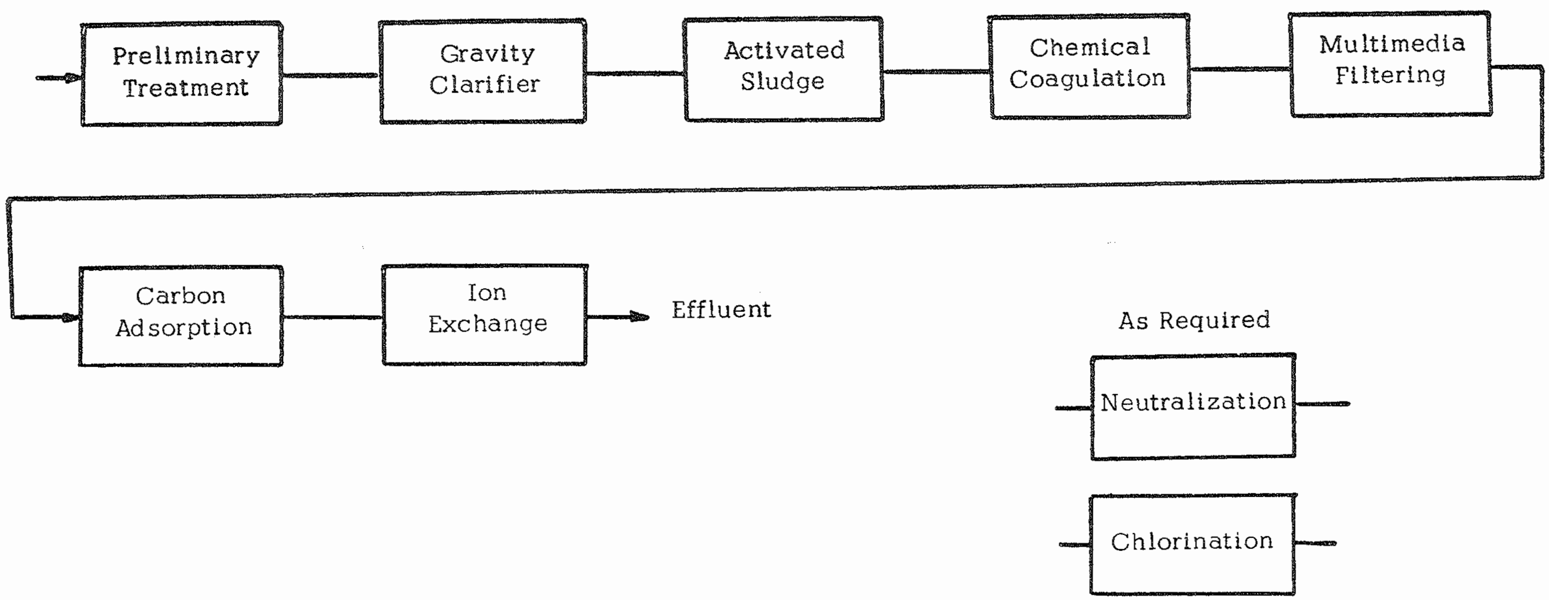


FIGURE 4.3
TREATMENT SYSTEM

Equations are of the form cost = A x $(\text{flow})^B$, where flow is in MGD and cost in cents/1000 gallons of water treated.

Process	A	B	Reference
1. Preliminary Treatment	0.54	-0.45	42
2. Gravity Clarifier	21.7	-0.24	42
3. Activated Sludge	14.5	-0.16	42
4. Chemical Coagulation	7.44	-0.05	42
5. Multimedia Filter	14.5	-0.36	42
6. Carbon Adsorption	32.8	-0.31	42
7. Ion Exchange	90.0	-0.25	43
8. Chlorination	2.23	-0.15	42
9. Neutralization	4.28	-0.43	44

TABLE 4.2
COST EQUATIONS

	Process	SS	BOD	TDS	Reference
1.	Preliminary Treatment	10			45
2.	Gravity Clarifier	75	40	10	46
3.	Activated Sludge	60*	90	30	45,46
4.	Chemical Coagulation	70	83	20	45
5.	Multimedia Filter	85	60		45
6.	Carbon Adsorption	85	80		45
7.	Ion Exchange		50	97	45

* Estimate

TABLE 4.3
REMOVAL EFFICIENCIES (PERCENT)

The unit cost of treatment for a specified percent removal for BOD, SS, and TDS at a 1 MGD plant is presented in Figure 4.4. This figure is based on the data presented in Tables 4.2 and 4.3. Most of the BOD and SS can be removed at relatively low costs, while TDS removal is expensive. This high cost of TDS removal is possibly the biggest obstacle to reuse of wastewater in the Corpus Christi area. Municipal wastewater has a TDS content of about 2000 mg/l, which is too high for direct reuse by most industries in the area. This value cannot be reduced to a more reasonable number (about 500 mg/l) without the use of expensive ion exchange columns. Results obtained with the model indicate that TDS is indeed the critical parameter before a closed-cycle system can be implemented in this area.

The required treatment sequences were based on the effluent of one user and the intake requirements of others in the vicinity. Industrial effluents were not acceptable for municipal use because of the possible presence of toxic materials. The effluent characteristics and water loss of the various users are summarized in Table 4.4. Intake requirements and cost of fresh water are given in Table 4.5. These data were developed from the best data available from state and federal agencies. Primary sources included the Army Corps of Engineers Permits to Discharge to Navigable Waters (~ 1970), the Texas Water Quality Board self-reported discharges, and water use data available through the Texas Water Development Board. Some estimates of quality, in-house use categories, and quantity of fresh water used were made where data were not available. The figures represent averages but correspond well with secondary data obtained to verify the primary sources.

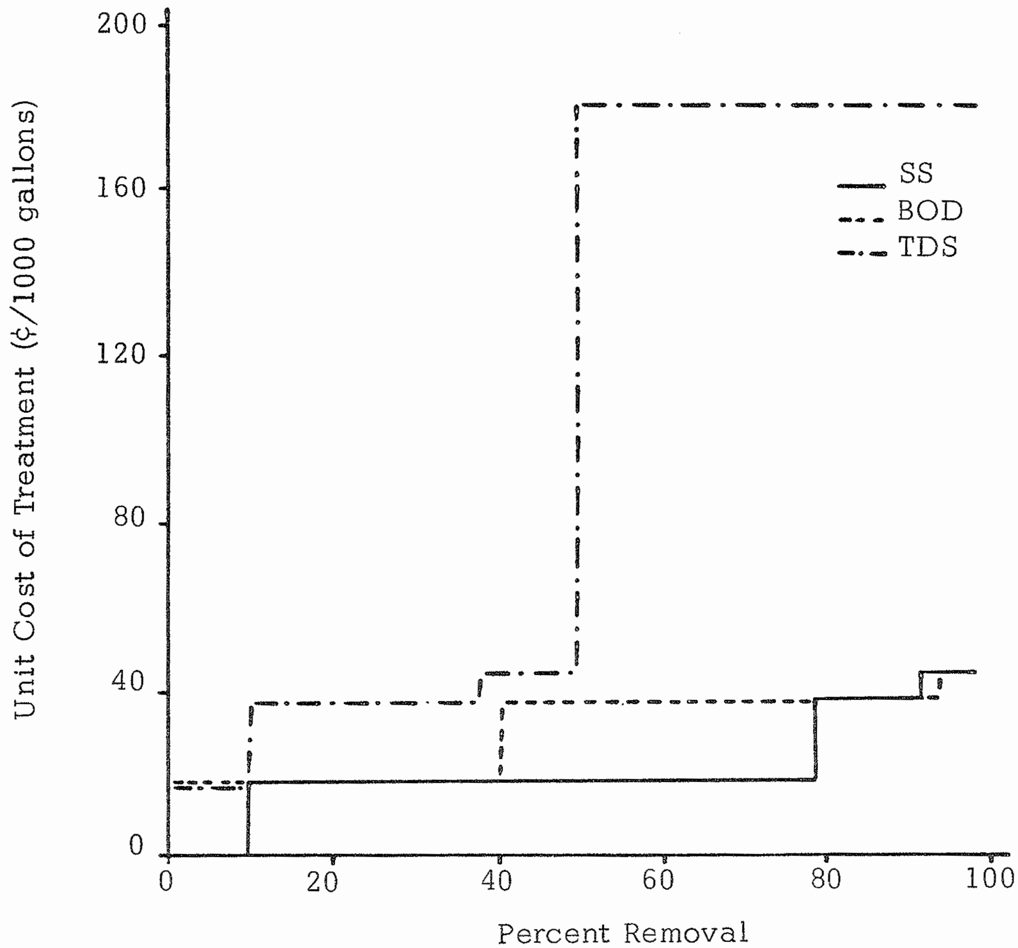


FIGURE 4.4
PERCENT REMOVAL VS. COST

User	Effluent Characteristics BOD	SS	TDS	Water Loss (%)
Industry 1	20	115	4,400	64
Industry 2	622	935	3,600	42
Industry 3	16	22	5,752	32
Industry 4	*	*	*	100
Industry 5	20	27	7,679	64
Industry 6	48	38	1,285	65
Industry 7	9	4	305	24
Industry 8	18	22	4,334	67
Industry 9	88	90	2,026	72
Industry 10	4	23	36,000	33
Industry 11	*	*	*	100
Industry 12	13	4	6,510	39
Industry 13	30	100	4,900	80
Corpus Christi	22	48	2,000	35
Robstown	54	68	2,000	64
Alice	30	17	2,000	64
Odem	54	117	2,000	36
Taft	82	69	2,000	71
Gregory	122	54	2,000	43
Portland	14	54	2,000	- 4
Aransas Pass	14	38	2,000	- 4
Port Aransas	3	13	2,000	- 1
Ingleside	16	44	2,000	37
Mustang Island	20	20	2,000	33
Padre Island	20	20	2,000	33
Nueces Park	20	20	2,000	33

* No discharge

TABLE 4.4
EFFLUENT CHARACTERISTICS AND WATER LOSS

User	Intake Requirements BOD	SS	TDS	Flow	Water Cost (¢/1000 gal)
Industry 1	75	5	629	3.95	23
Industry 2	300	300	650	2.18	23
Industry 3	75	1,000	5,000	1.55	23
Industry 4	75	5	629	.25	35
Industry 5	75	5	629	4.34	23
Industry 6	75	5	629	.39	35
Industry 7	75	10	2,500	2.12	23
Industry 8	75	5	629	2.34	23
Industry 9	75	5	629	2.64	23
Industry 10	75	1,000	20,000	.33	35
Industry 11	50	20	700	6.24	23
Industry 12	75	10,000	2,500	4.74	23
Industry 13	75	10,000	2,500	5.20	23
Corpus Christi	15	2	500	29.82	19
Robstown	15	2	500	2.18	23
Alice	15	2	500	3.91	19
Odem	15	2	500	.25	35
Taft	15	2	500	.48	35
Gregory	15	2	500	.21	35
Portland	15	2	500	.87	23
Aransas Pass	15	2	500	1.00	23
Port Aransas	15	2	500	.52	35
Ingleside	15	2	500	.40	35
Mustang Island	15	2	500	.01	41
Padre Island	15	2	500	.03	41
Nueces Park	15	2	500	.10	35

* No discharge

TABLE 4.5
INTAKE REQUIREMENTS AND WATER COST

PROJECTIONS FOR 1980 AND 1990

The fresh water requirements (as opposed to demand) for all users in the area was determined from industrial and municipal growth projections and are shown in Tables 4.6 and 4.7. These tables also show the projected effluent characteristics. The 1980 figures assume that the application of Best Practicable Control Technology Currently Available (BPCTCA) for industrial wastewaters will take place and that all municipalities will at least be meeting the current State of Texas requirement for BOD and SS. The 1990 projections assume that municipalities will at least be meeting a 12 mg/l BOD and 9 mg/l SS discharge requirement. Although it is the national goal that there shall be no discharge of pollutants to the navigable waters of the Nation by 1985, it is assumed that industry will just meet the requirements of Best Available Technology Economically Achievable (BATEA), which are scheduled to take effect in 1983.

PROGRAM DESCRIPTION

A general flow chart for the program used is shown in Figure 4.5. Detailed flow charts for the main program and associated subroutines are given in Appendix II. A full listing is given in Appendix I.

The program starts by quantifying the water that can be transferred under existing geographical constraints, identifying the potential users for this water and determining the cost function for each of the possible transfers. A typical output print from this initial determination is shown in Table 4.8. Once the feasible transfers and recycles are determined, a determination is made as to the number of constraints and variables. The number of constraints is equal to twice the number of users plus one. The number of variables depends on the possible

User	Effluent Characteristics (mg/l) BOD	SS	TDS	Flow Requirement (MGD)
Industry 1	13	9	3,520	4.82
Industry 2	33	23	1,800	2.67
Industry 3	10	9	4,602	1.87
Industry 4	*	*	*	0.31
Industry 5	15	10	6,143	5.30
Industry 6	31	21	1,028	0.48
Industry 7	9	4	305	2.86
Industry 8	15	10	3,467	2.86
Industry 9	36	24	1,418	3.22
Industry 10	4	7	28,800	0.42
Industry 11	*	*	*	7.52
Industry 12	7	6	5,208	6.39
Industry 13	7	6	3,920	7.01
Corpus Christi	20	20	2,000	31.35
Robstown	20	20	1,400	2.60
Alice	20	17	2,000	3.46
Odem	20	20	1,400	0.25
Taft	20	20	1,400	0.41
Gregory	20	20	1,400	0.20
Portland	14	20	2,000	1.16
Port Aransas	3	13	2,000	0.59
Ingleside	16	20	2,000	0.40
Mustang Island	20	20	2,000	0.02
Padre Isles	20	20	2,000	0.06
Nueces Park	20	20	2,000	0.12
Aransas Pass	14	20	2,000	0.98

* No discharge

TABLE 4.6
1980 PROJECTIONS

User	Effluent Characteristics (mg/l) BOD	SS	TDS	Flow Requirement (MGD)
Industry 1	8	8	3,520	6.11
Industry 2	13	9	1,800	3.40
Industry 3	10	9	4,602	2.35
Industry 4	*	*	*	0.39
Industry 5	11	8	6,143	6.72
Industry 6	22	15	1,028	0.61
Industry 7	3	3	244	3.91
Industry 8	11	8	3,467	3.63
Industry 9	9	9	1,134	4.08
Industry 10	4	7	28,800	0.56
Industry 11	*	*	*	9.43
Industry 12	7	6	5,208	8.73
Industry 13	7	6	3,920	9.58
Corpus Christi	12	9	1,600	38.96
Robstown	12	9	1,120	2.53
Alice	12	9	1,600	2.45
Odem	12	9	1,120	0.25
Taft	12	9	1,120	0.24
Gregory	12	9	1,120	0.10
Portland	12	9	1,600	1.60
Port Aransas	3	9	1,600	0.83
Ingleside	12	9	1,600	0.35
Mustang Island	12	9	1,600	0.06
Padre Isles	12	9	1,600	0.13
Nueces Park	12	9	1,600	0.13
Aransas Pass	12	9	1,600	0.85

* No discharge

TABLE 4.7
1990 PROJECTIONS

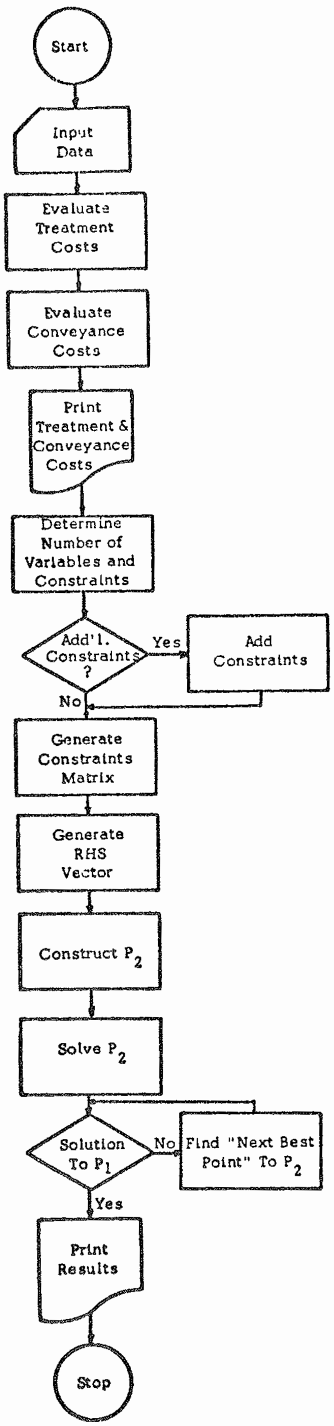


FIGURE 4.5
GENERAL PROGRAM FLOW CHART

From cost and distance considerations the following alternatives are considered feasible:

From	To	Treatment Cost Equation (¢/1000 gal)	Conveyance Cost (¢/1000 gal)
Industry 1	Industry 3	0.0	5.1 x Flow ** -0.505
Industry 2	Industry 3	38.2 x Flow ** -0.242	1.4 x Flow ** -0.505
Industry 3	Industry 3	7.7 x Flow ** -0.050	0.0 x Flow ** -0.505
Industry 4	Industry 3	0.0	2.2 x Flow ** -0.505
	Industry 7	22.8 x Flow ** -0.202	0.7 x Flow ** -0.505
Industry 5	Industry 3	7.7 x Flow ** -0.050	3.4 x Flow ** -0.505
	Industry 7	22.8 x Flow ** -0.202	1.1 x Flow ** -0.505
Industry 6	Industry 3	0.0	3.1 x Flow ** -0.505
Industry 7	Industry 1	0.0	7.5 x Flow ** -0.505
	Industry 2	0.0	3.9 x Flow ** -0.505
	Industry 3	0.0	2.6 x Flow ** -0.505
	Industry 4	0.0	0.7 x Flow ** -0.505
	Industry 5	0.0	0.0 x Flow ** -0.505
	Industry 6	0.0	0.7 x Flow ** -0.505
	Industry 7	0.0	1.1 x Flow ** -0.505
	Industry 8	0.0	2.1 x Flow ** -0.505
	Industry 9	0.0	1.5 x Flow ** -0.505
Corpus Christi	Industry 3	0.0	4.4 x Flow ** -0.505
	Industry 7	22.8 x Flow ** -0.202	4.1 x Flow ** -0.505

Maximum Distance Allowed: 10 miles

TABLE 4.8
WATER ALLOCATION MODEL RESULTS

transfers. At this point the program has the capability to allow for the introduction of more constraints and any other constraints as to the feasibility of a particular transfer. The number of constraints and variables is re-evaluated if necessary and the constraints matrix and right-hand side vector is automatically generated. From the cost functions determined initially, the coefficients of the cost function of problem P_2 are determined, and P_2 is solved with a call to Subroutine SIMPLE. The Cabot and Francis Algorithm is used iteratively at this point to search the constraint polyhedron until the vertex at which P_1 is a minimum is found. An optimal solution is found and the results are printed out. A typical output printout is shown in Table 4.9.

As given by Equation 3.5, none of the variables in the model have an upper bound. The formulation of P_2 requires an upper bound on the variables that enter into the non-linear functions of P_1, namely the X's. From Equation 3.2 it may be seen that $X_{n,i}$ has D_n as an upper bound for all i. Upper bounds for Q_n or Z_n are not required, although Q_n has D_n as an upper bound.

The parameters pH and Total Coliforms are considered in the determination of the cost functions. pH was not a factor in this area since all the effluents reported pH range between 6.0 and 9.0. Because all the municipal effluents were chlorinated and no transfers from industries to municipalities were permitted, Total Coliforms was not a significant factor in considering industrial use of the municipal treated effluents for boiler and cooling water make-up.

EVALUATION OF DIFFERENT POLICIES

The objective of this study was the development of a

User to User Water Reuse:

From	To	Amount of Water (1000 gal)
Industry 6	Industry 3	772
Corpus Christi	Industry 3	778
Industry 5	Industry 8	250
Industry 5	Industry 4	390
Corpus Christi	Industry 5	2,120
Industry 5	Industry 6	971

User	Water Intake (1000 gal)	Effluent (1000 gal)
Industry 1	3,950	1,422
Industry 2	2,180	1,264
Industry 3	0	1,054
Industry 4	0	136
Industry 5	0	0
Industry 6	1,369	0
Industry 7	2,640	739
Industry 8	0	0
Industry 9	4,340	1,562
Corpus Christi	29,824	16,488

Total Cost for this system is: 9,560.00 dollars/day

TABLE 4.9

EXAMPLE PRINTOUT

model to determine the future demand of fresh water in the Corpus Christi area, to evaluate policies designed to reduce that total demand, and to estimate costs. The model has been described previously and the analysis is discussed at this point.

The future water requirement for the area is shown in Figure 4.6 as "requirements", or the amount of water withdrawn from the fresh water source if no recycling or no transfers of water were to take place. The "demand", or the amount of water actually withdrawn if the system as a whole were to optimize water use under the concept of the basin-wide firm, also is shown in Figure 4.6. Considering only the requirements, by the year 1995 the safe yield of Lake Corpus Christi would be exceeded just by the projected growth of the industries and municipalities currently located in the region. The establishment of any new industry, particularly a high water user, would only accelerate the trend. At the present time construction of the Choke Canyon Reservoir has not started and there is considerable doubt that the reservoir will be constructed; therefore, it seems a water shortage in the area probably will develop.

However, when demand is considered, the situation is improved somewhat. In 1974 users were not making optimal use of the available water resource and a reduction of the total fresh water intake was possible by a few interindustry transfers. This reduction would have amounted to about 10% of total fresh water intake. In 1980 the application of BPCTCA will result in better quality effluent. In this year a reduction of about 11% of total fresh water intake is feasible. The application of BATEA in 1983 will bring about still better quality effluents, and by 1990 a reduction in the fresh water withdrawal of about 12% is possible. These transfers do not require any additional

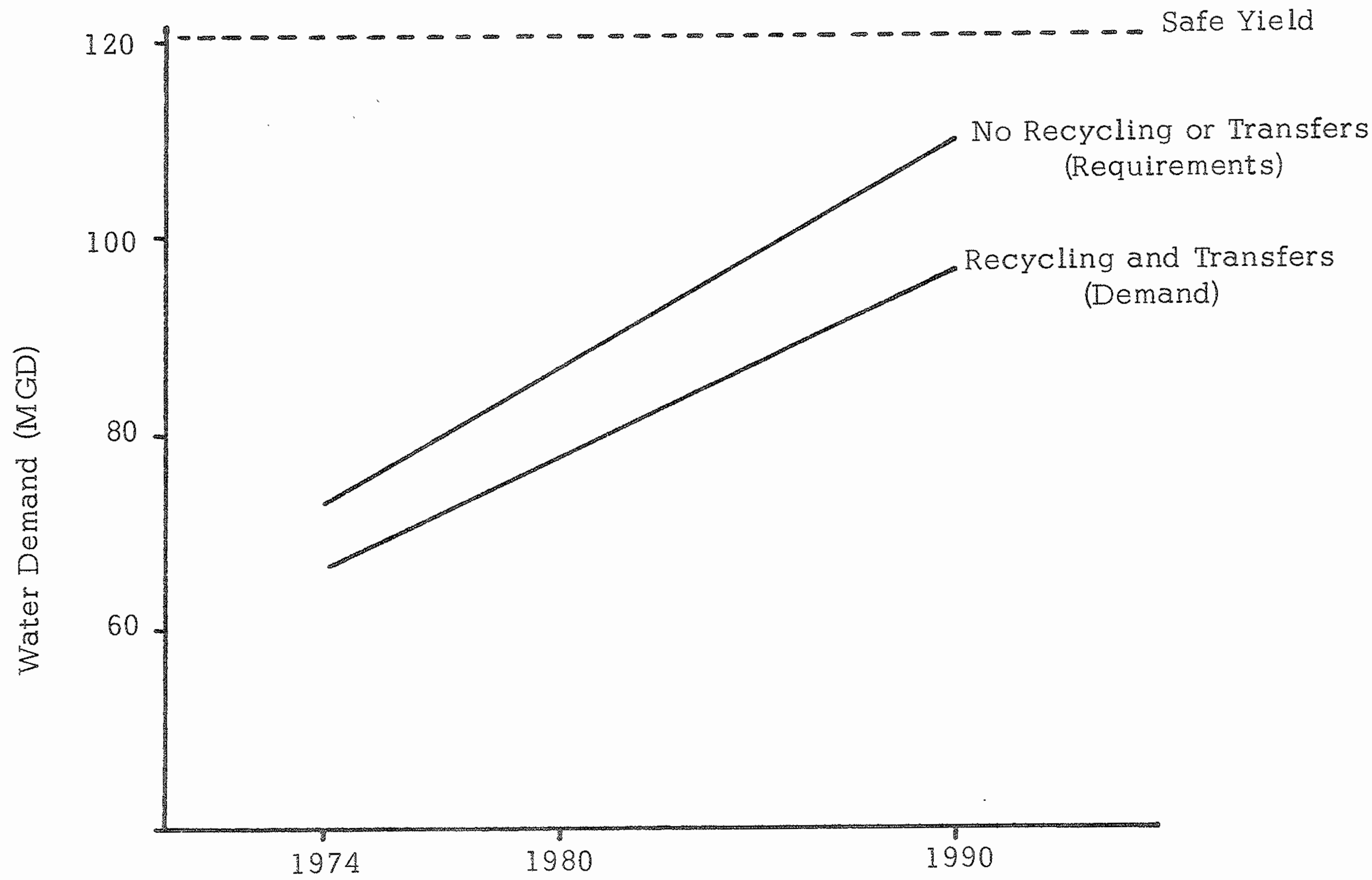


FIGURE 4.6
FUTURE WATER DEMAND

treatment costs for the users, but simply represent the optimal utilization of water in the area.

The data presented in Table 4.4 indicate that transfers of water are currently feasible and economical. The effluent from Industry 7 is of good quality, and as seen in Table 4.5, meets the intake requirements of all otherindustries in the area. Distance is the only constraint for some transfers. A number of other zero-cost transfers are possible, and the number increases for the 1980 and 1990 data.

In case a further decrease in fresh water demand is desired, the effects of three different policies were evaluated, namely:

I. Increase the price of water for all users
II. Increase the price of water for all industrial users
III. Impose a unit charge for wastewater discharged by industries

The application of Policy I would mean a uniform increase in the cost of water for all users. Since users are now paying different unit rates, this Policy would increase costs proportionally for everyone. That is, the actual unit rate would be multiplied by a common factor until the desired results are achieved.

The results of applying Policy I for the years under consideration are shown in Figures 4.7, 4.8, and 4.9. These figures show the amount of fresh water withdrawn by the entire system and the total effluent discharged to the receiving waters. Generally, the first reduction in water withdrawal occurs when the unit rate is increased by about a factor of 4.5. At this point a few inter-user transfers become economical. These transfers are from small municipalities

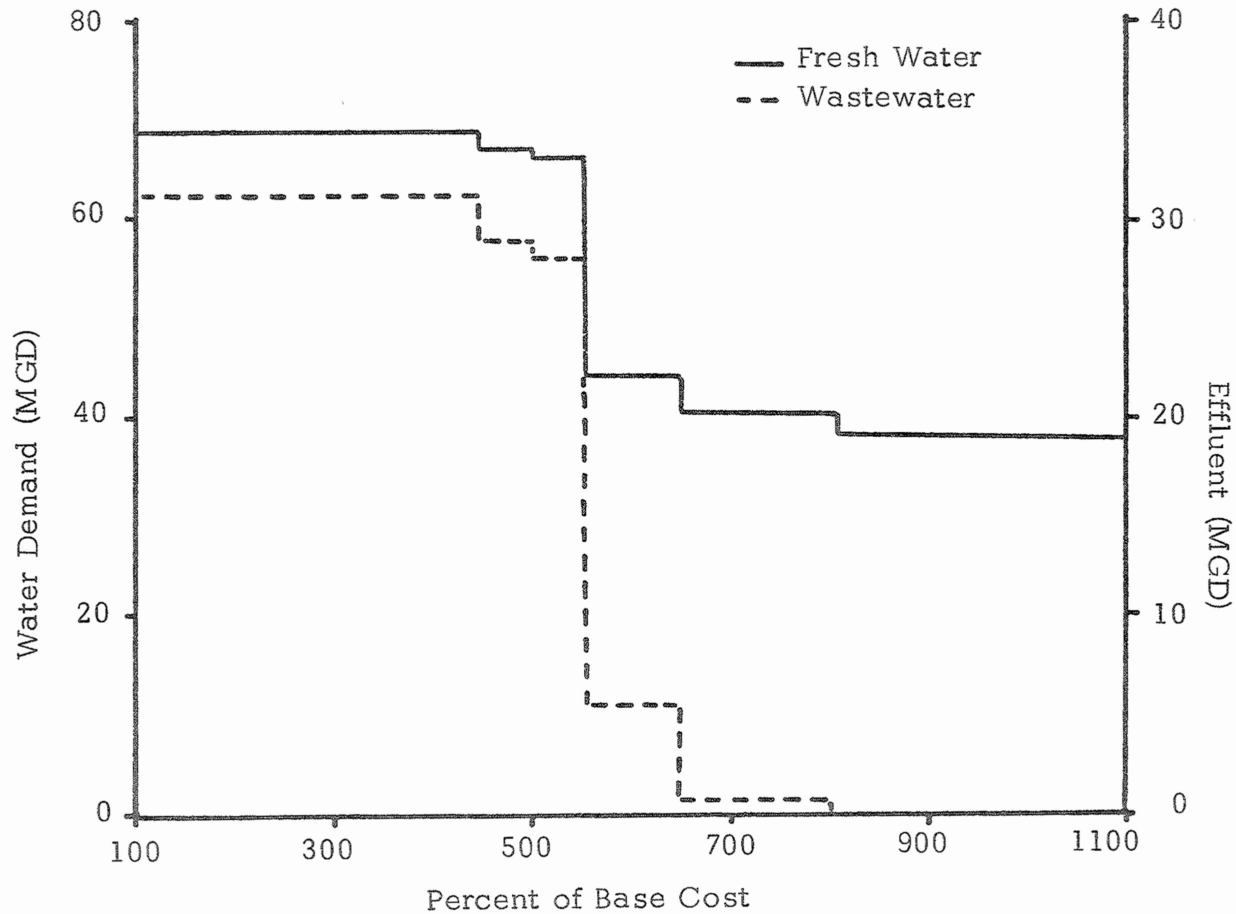


FIGURE 4.7
APPLICATION OF POLICY I (1974)

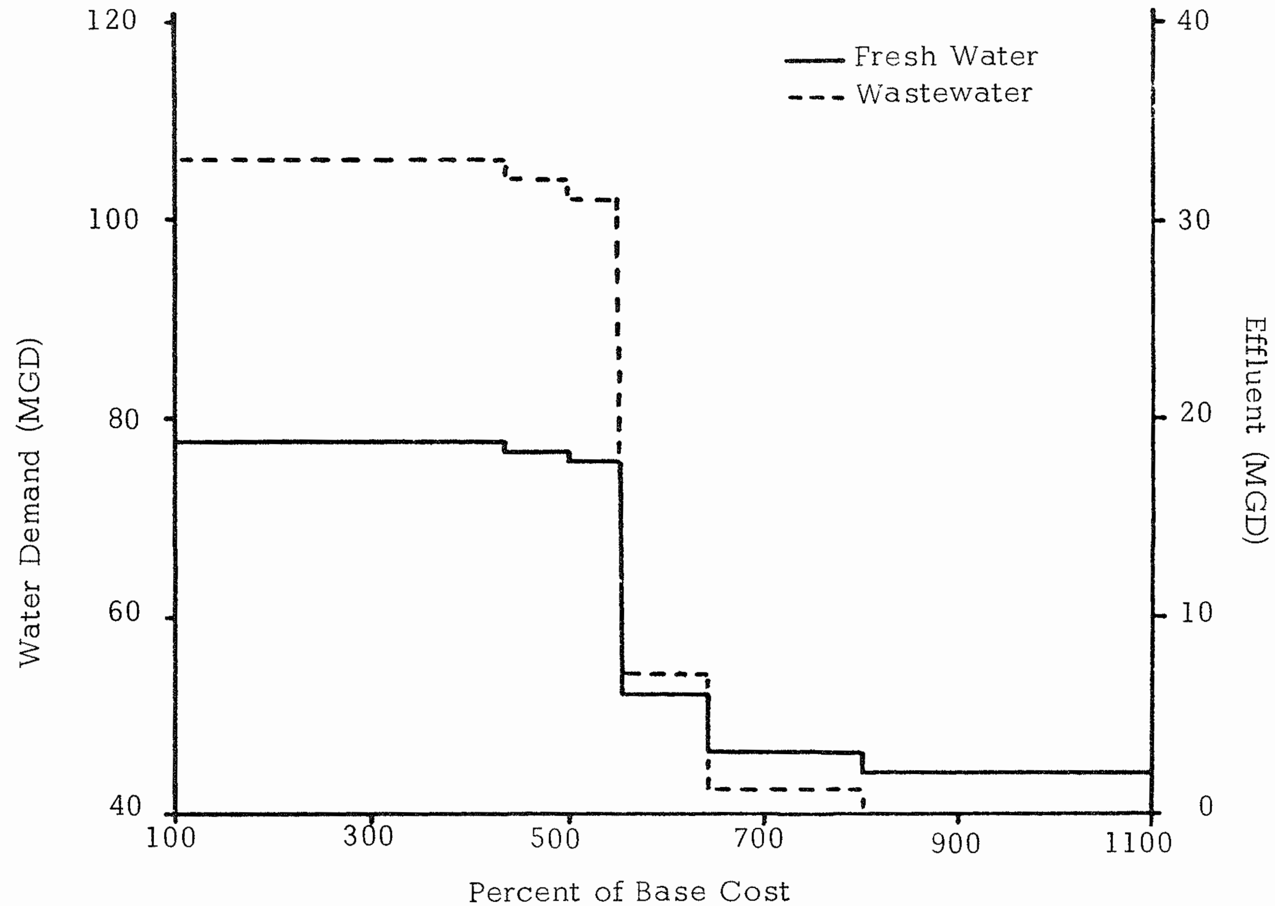


FIGURE 4.8
APPLICATION OF POLICY I (1980)

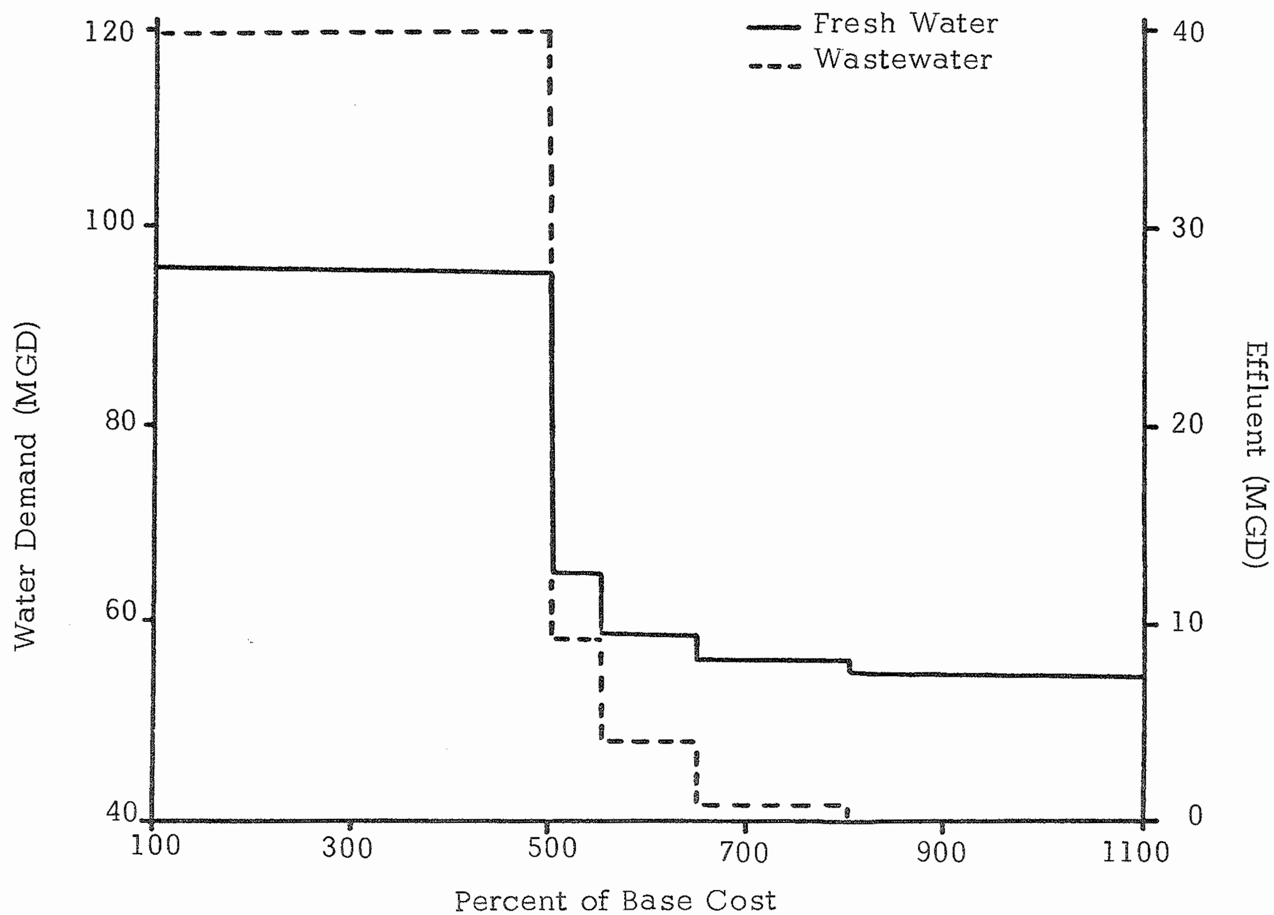


FIGURE 4.9
APPLICATION OF POLICY I (1990)

to industries. At an increase by a factor of 5, a few other small transfers take place, including a total recycle by one of the small municipalities. The most significant reduction occurs at a factor of 5.5, when the City of Corpus Christi goes to total recycling and transfer of wastewater and almost all industries recycle or transfer. At this point the wastewater discharged comes from one single industry and some municipalities. This industry does not go into total recycle until the price of water is increased by a factor of 6.5. The final municipality recycles at a factor of 8.0, and at this point the system is at maximum utilization of the water resource. Zero Discharge for Wastewater is achieved.

The main obstacle to water transfers at small increases in water cost is the TDS concentration. The cost of treatment of wastewater for TDS removal is in the vicinity of $1.75/1000 gallons at the 1 MGD level. Once the "easy" transfers are made when the difference between "requirements" and "demand" is considered, very few other transfers are possible until the TDS level is reduced. This factor is particularly important in the area under consideration, where the municipal wastewater has a TDS concentration of approximately 2000 mg/l.

The results obtained when Policy II is applied are summarized in Figures 4.10, 4.11, and 4.12. This Policy is similar to Policy I, but only industries pay more for the water. This increase is in the form of charging all industries the same unit rate, independent of the amount of water used. Reduction in consumption occurs in two steps. At a unit rate of $1.50/1000 gallons, industries start to use recycled water, mainly from the Corpus Christi wastewater treatment plant. At $1.75/1000 gallons, all industries that could use municipal water

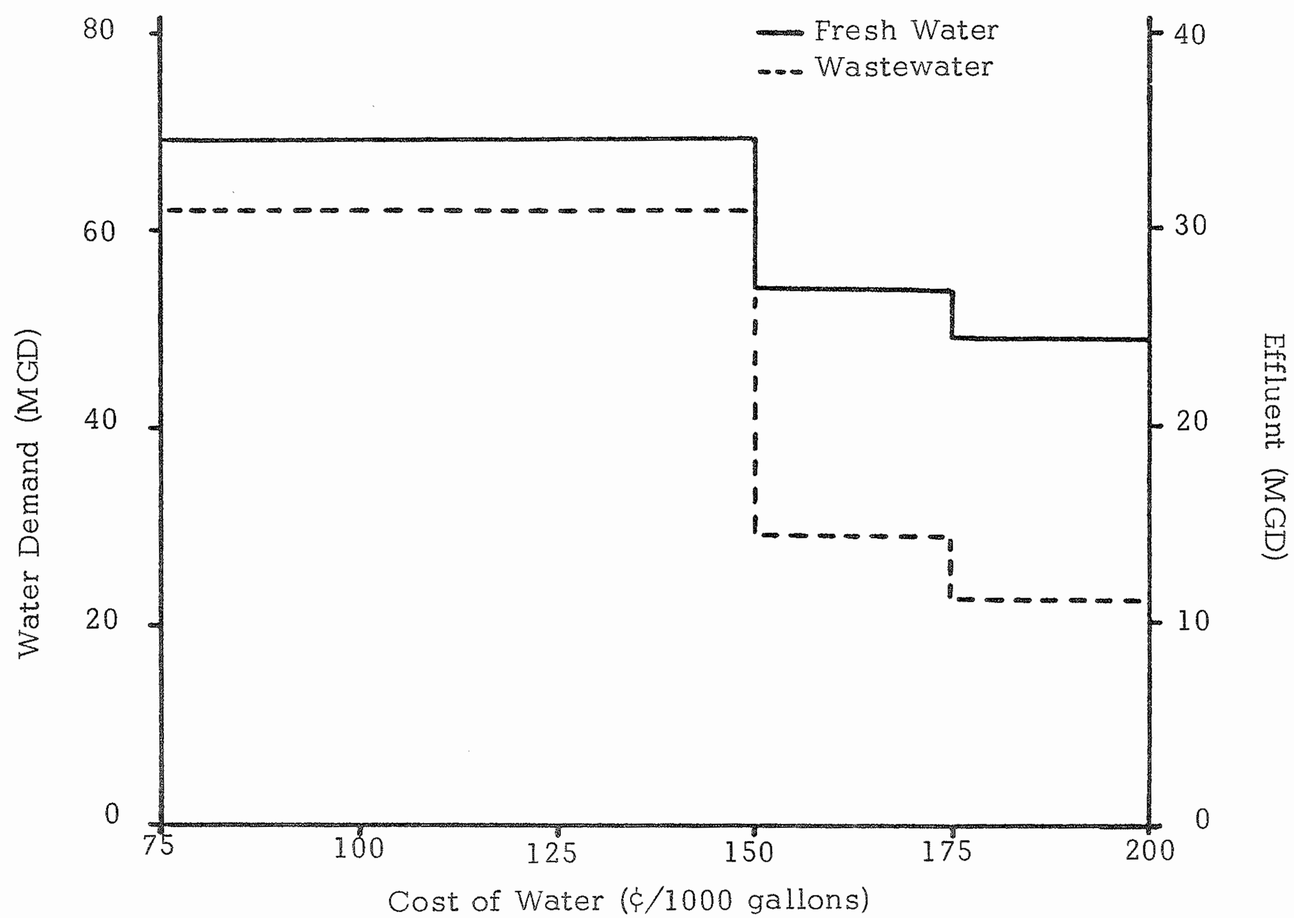


FIGURE 4.10
APPLICATION OF POLICY II (1974)

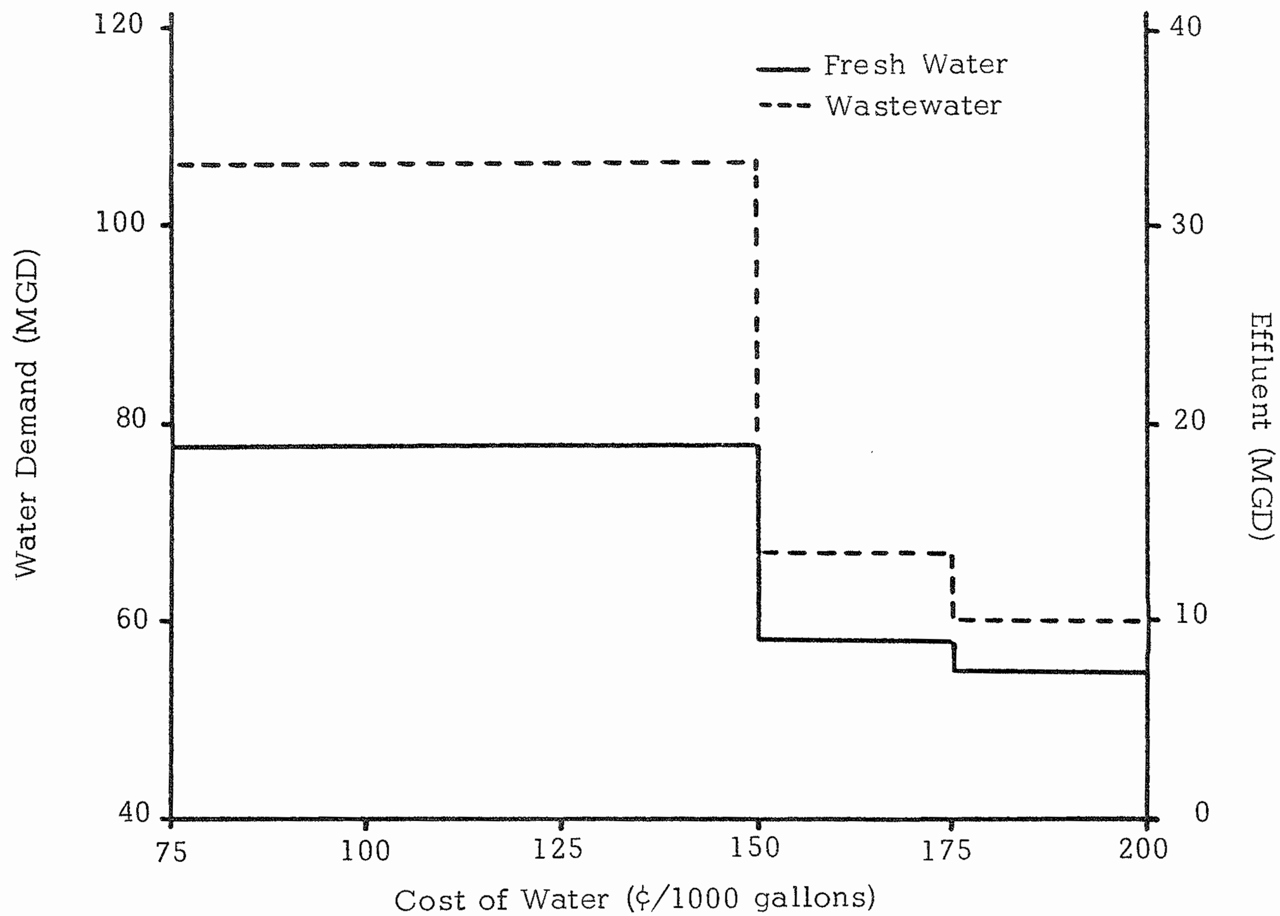


FIGURE 4.11
APPLICATION OF POLICY II (1980)

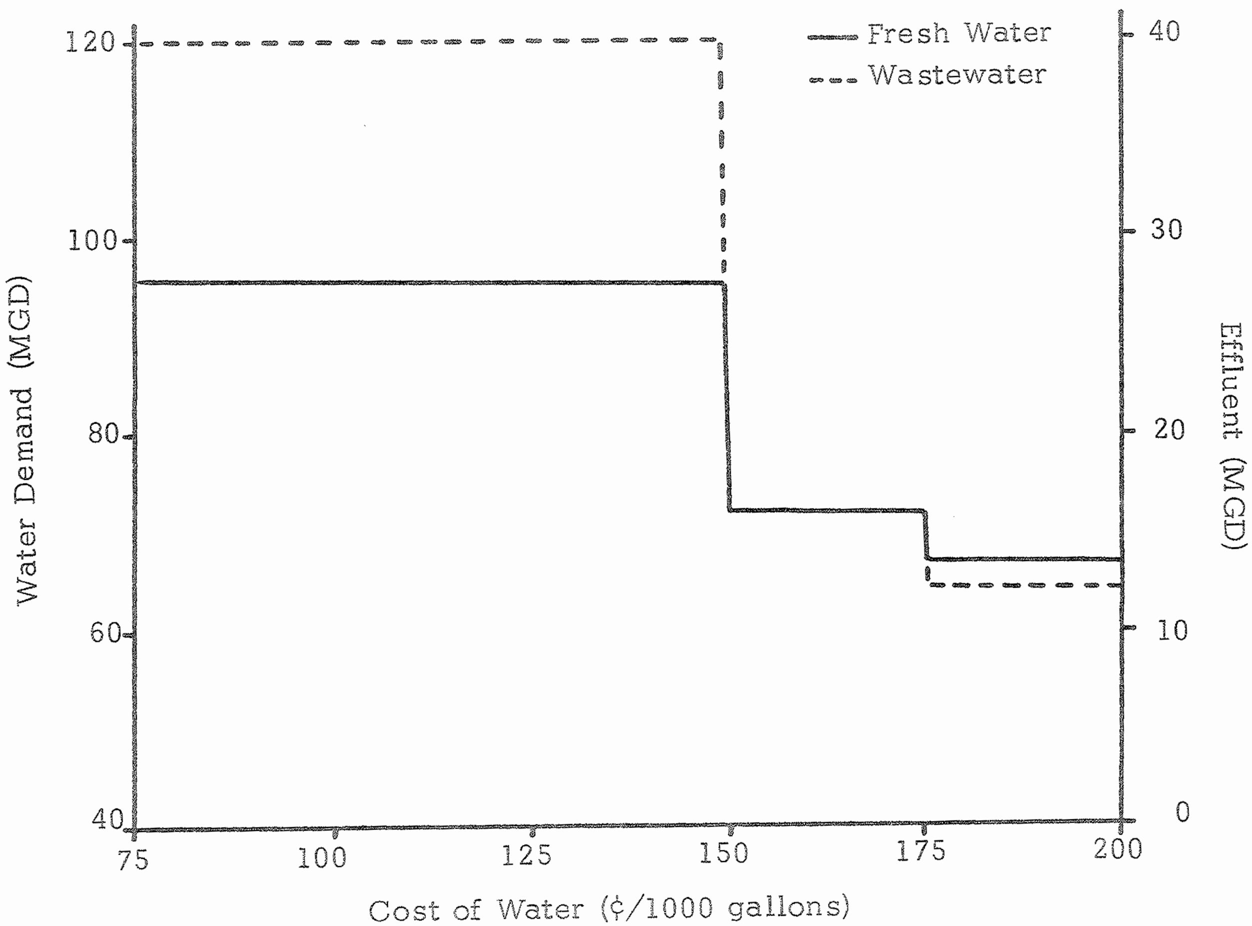


FIGURE 4.12
APPLICATION OF POLICY II (1990)

have done so and have also made all the possible interindustry transfers. At this point of maximum reuse, the wastewater discharged is about one-third of that discharged if Policy II is not applied. This Policy never leads to Zero Discharge because there is no incentive for municipalities to reuse their own wastewater. Zero Discharge of Industrial wastewater is achieved.

Policy III considers a different approach. Instead of increasing costs of fresh water, the cost of disposal is increased by imposing a unit charge on the amount of industrial wastewater discharged. This charge can be set to relate to the amount of pollutants in the effluent, but will be allocated in terms of cents/1000 gallons of wastewater discharge. A charge based on cents/pound of pollutant discharged is not only very difficult to handle mathematically, but also tends to encourage further treatment and discharge rather than transfer and reuse.

The effects of the application of Policy III are shown in Figures 4.13, 4.14, and 4.15. With this Policy a single reduction in demand occurs, in the vicinity of a charge of $1.25/1000 gallons discharged. At this point interindustry transfer of all effluents occurs. However, very little of the municipal wastewater is reused because once industries arrive at Zero Discharge, no economic incentive to reuse municipal wastewater exists and the cost for fresh water does not increase. This policy causes a reduction in wastewater discharged to about two-thirds of the base case.

A comparison of the three policies with respect to cost is presented in Figures 4.16, 4.17, and 4.18 for each of the years 1974, 1980, and 1990. Policy I is the most expensive, followed by Policy II

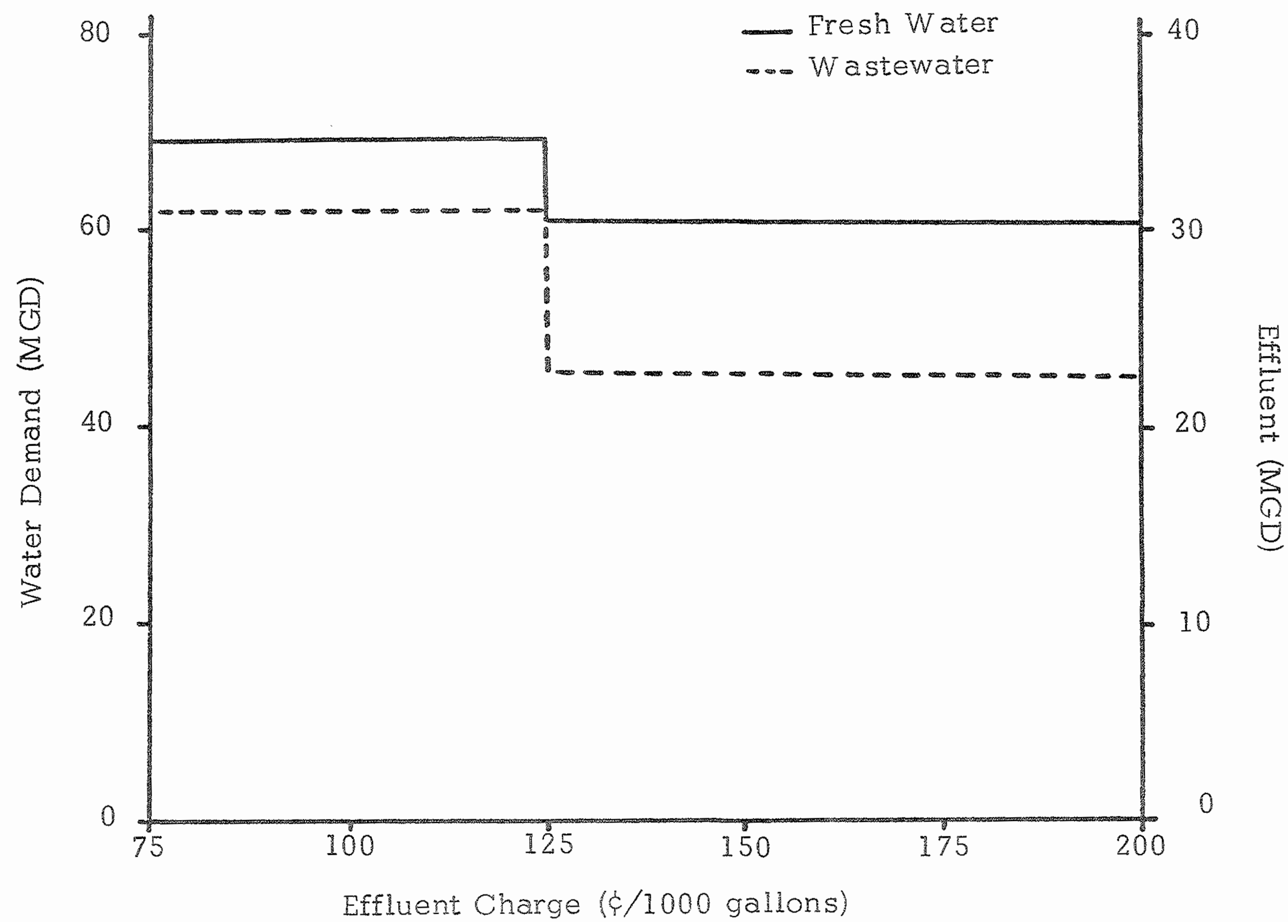


FIGURE 4.13
APPLICATION OF POLICY III (1974)

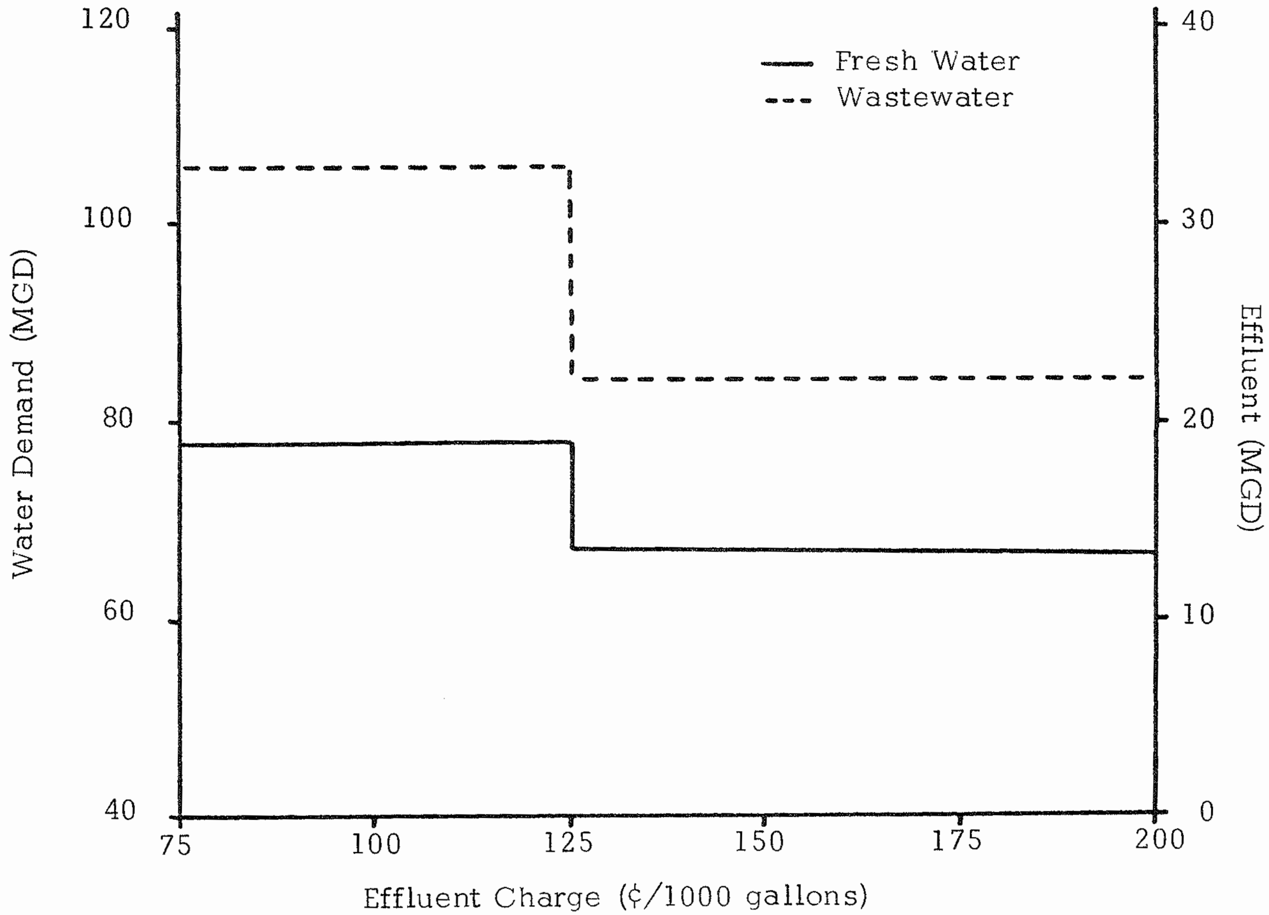


FIGURE 4.14
APPLICATION OF POLICY III (1980)

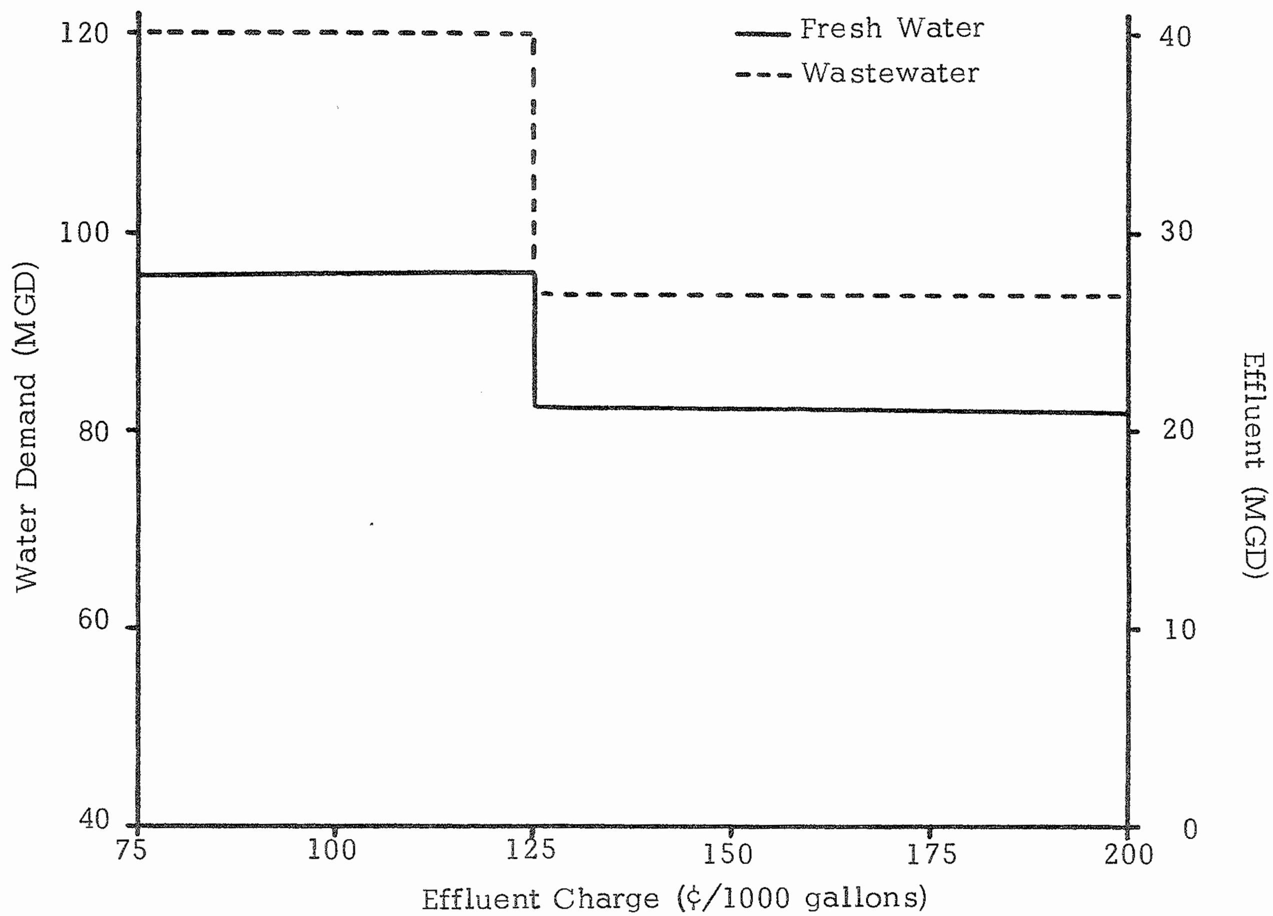


FIGURE 4.15
APPLICATION OF POLICY III (1990)

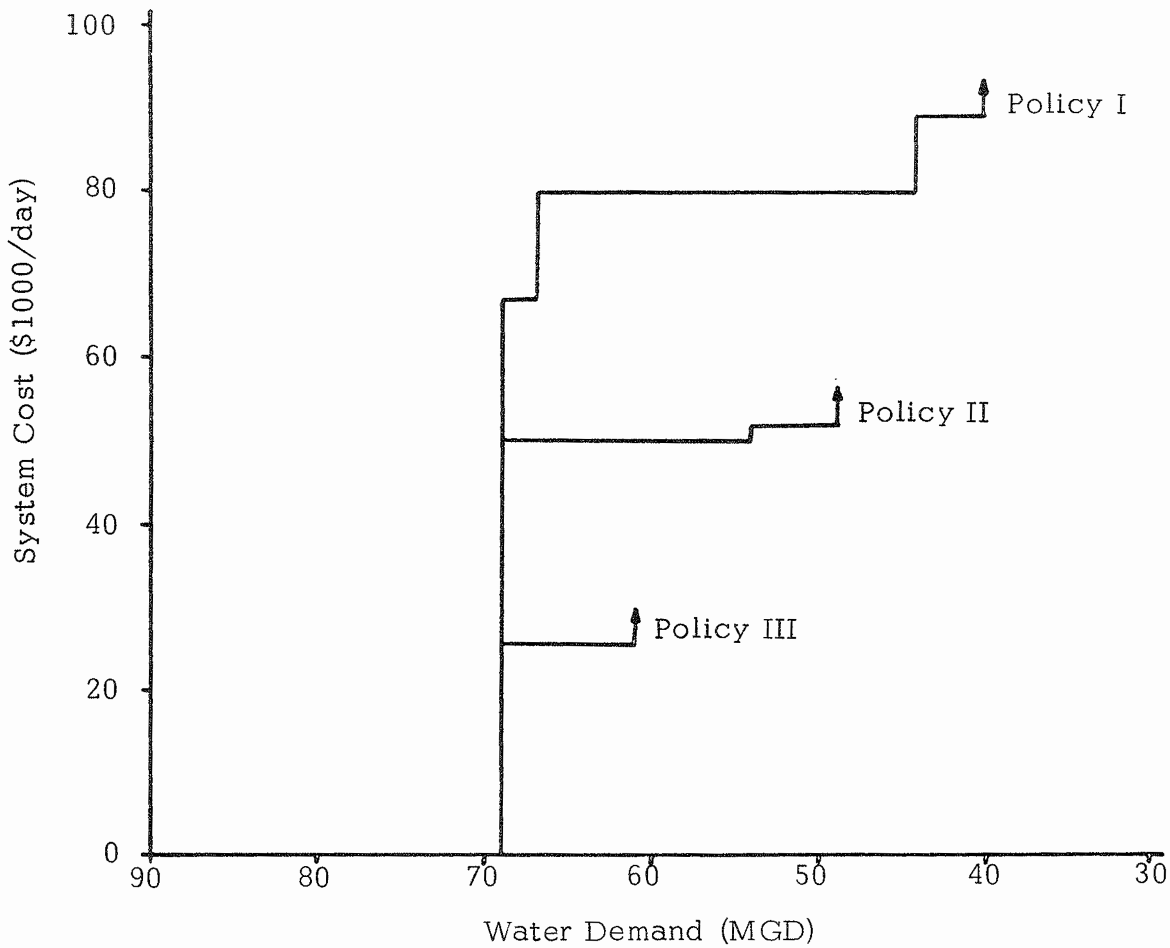


FIGURE 4.16
COST COMPARISONS OF POLICIES (1974)

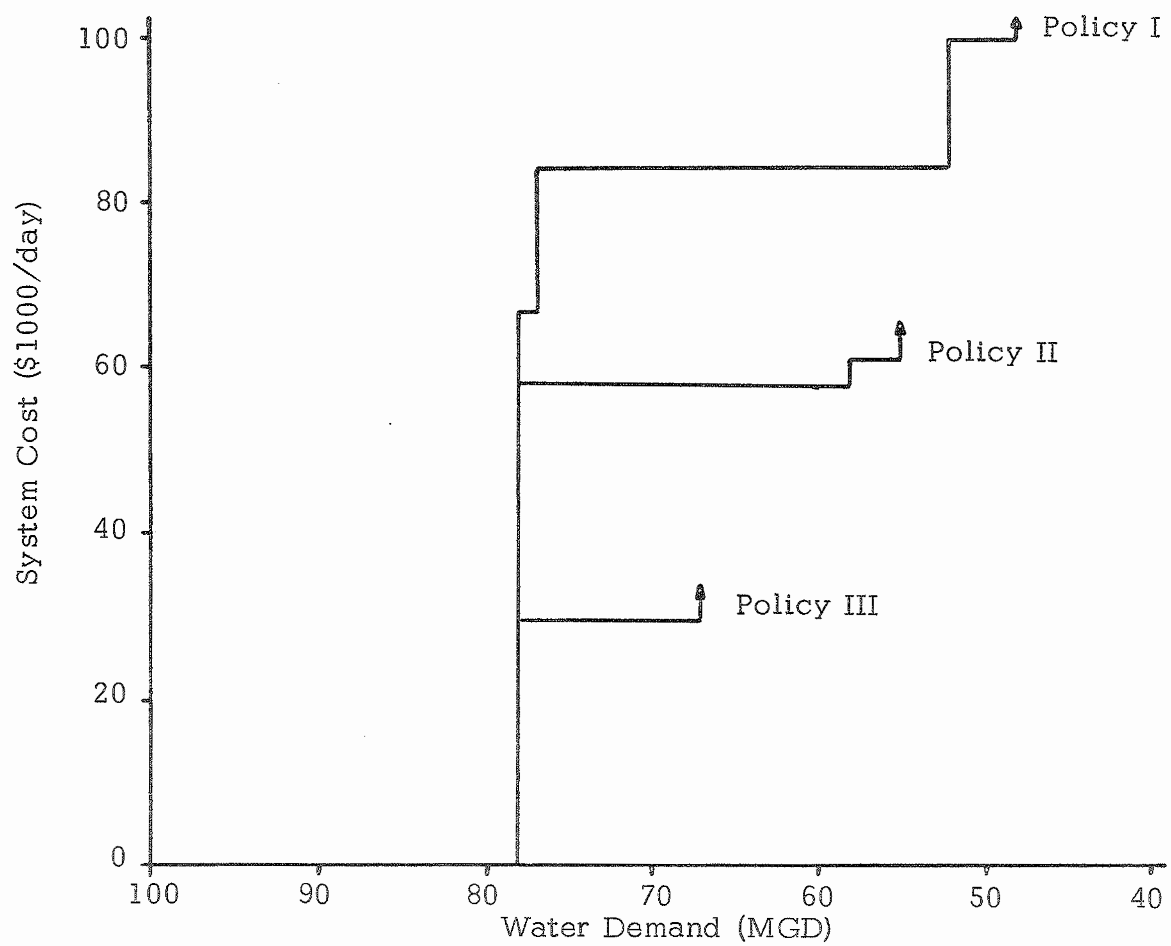


FIGURE 4.17
COST COMPARISON OF POLICIES (1980)

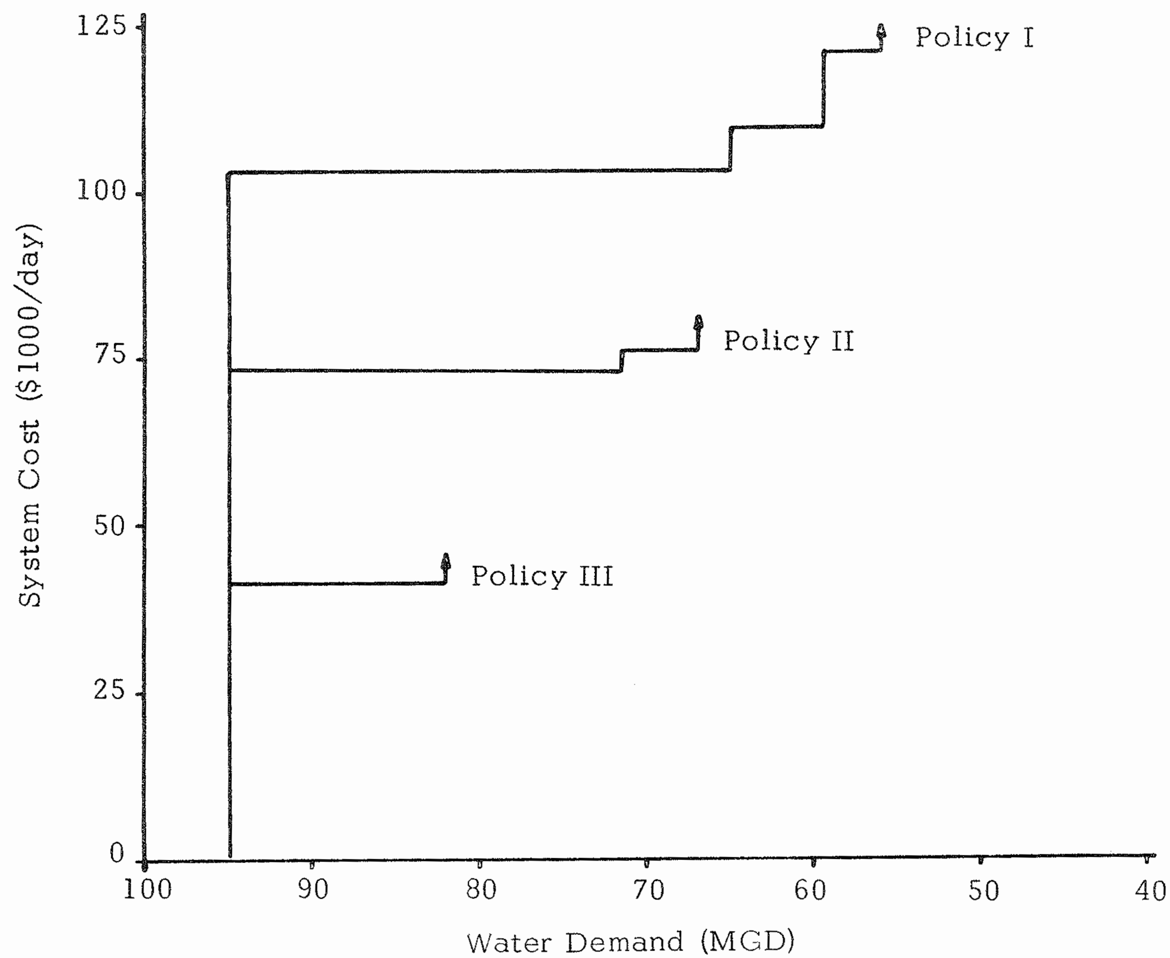


FIGURE 4.18
COST COMPARISON OF POLICIES (1990)

and Policy III. Policy I also causes the largest reduction in demand and forces the system to go to Zero Discharge. The reduction in demand attainable with each policy is shown in Figure 4.19. As the required reduction increases, the cost for the system also is considerably increased.

The total cost of fresh water and wastewater treatment by industrial sectors for the Corpus Christi area for the years 1974, 1980 and 1990 is presented in Table 4-10. The direct requirement coefficient (DRC) for 1974 also is shown. These figures were calculated using the treatment sequence given in Figure 4.3 and the cost functions given in Table 4.2. If Policy II is applied to the system in 1974 in order to reduce demand to 49 MGD, the cost is $51,000 per day, or $18.6 million per year. This cost represents an increase of about 3 1/3 times in the cost of wastewater treatment. However, the DRC with this policy would be increased to 0.022, which is about a factor of 4. The application of Policy III to reduce the demand to 61 MGD causes an increase in the DRC to 0.014. Although the increases in the DRC are significant, the value is still small when compared to the DRC's associated with other production factors such as labor, raw materials, and energy.

A fourth alternative for demand reduction in the area is the use of saline water for cooling. The model can be used for estimating these savings by dividing each user in two parts, one comprising the requirements for process and sanitary water and the other the requirements for cooling water. This approach would increase the industrial users in the area by a factor of 2, causing a considerable increase in both the constraints and the variables to be optimized in the non-linear program. At this time computer resources make it

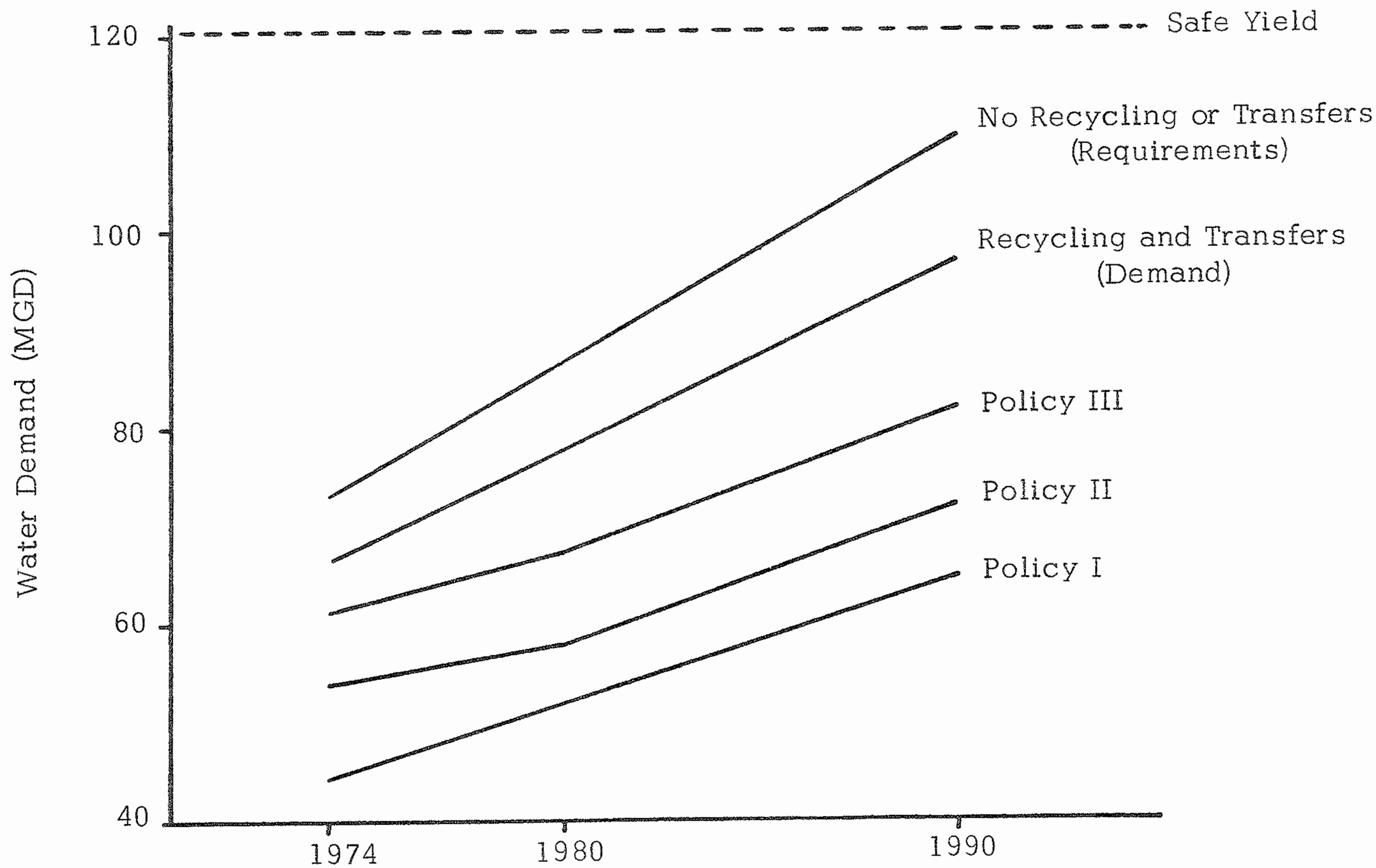


FIGURE 4.19
EFFECT OF DIFFERENT POLICIES

Sector	Description	Total 1974 Output ($1000)	1974 Wastewater Treatment ($1000)	1974 Water Cost ($1000)	DRC*	Additional Wastewater Treatment Cost ($1000) 1980	1990
20	Other food and kindred products	97,671	0	158	.0016	360	56
25	Chemicals, drugs and related products	344,813	1,140	868	.0058	515	770
26	Petroleum refining and related products	433,192	1,277	1,308	.0059	627	871
28	Cement and concrete products	26,949	58	28	.0031	12	16
29	Primary metals	176,615	187	561	.0042	49	61
	Total for five sectors	1,079,240	2,652	2,923	.0051	1,563	1,774

* DRC Direct Requirement Coefficient: Fraction of gross output represented by payments to water and wastewater sector.

TABLE 4.10
WATER AND WASTEWATER COSTS

impossible to consider such a procedure. However, limited data are available and the estimated reduction in requirements if saline water is used exclusively is 16 MGD in 1974 and 20 MGD and 26 MGD in 1980 and 1990 respectively.

The policies analyzed can be combined in a myriad of ways. These alternatives can be analyzed using the methodology which has been developed. A number of other socio-economic and political constraints enter into any type of decision that has to do with the water resource. The policymaker must consider all these constraints so that the proper combination of alternatives can be determined.

CHAPTER 5
DISCUSSION

The model developed in this study is based on the concept of the basin-wide firm introduced by Kneese and Bower (3). This concept postulates the existence of a single firm (or authority) that: directs all water-using industrial enterprises; is in charge of all water and wastewater treatment facilities; owns and operates all sources of water; and operates in competitive markets to maximize profits. For profit maximization, this firm selects the combination of water quality control measures that minimizes the overall system costs associated with wastewater disposal activities and water supply functions. Since this firm pays for all wastewater treatment facilities involved in making the effluent of one user suitable for use by another user, there is no need to allocate this expense to either user. The assumption of this firm allows for optimization of costs for the whole basin, since it is impossible to optimize for each individual user.

The application of the model to a particular area requires a number of assumptions with respect to the shape and size of the area in question. The area and number of users must be such that the limitations of the model are not exceeded. If the area is too large, it is necessary to assume certain boundaries in order to reduce size. These boundaries usually are based on natural barriers, such as in the Corpus Christi area, where natural constraints in the form of bodies of water can be used to divide users into smaller groups. A second possibility is a distance constraint that can be determined by the exercise of engineering judgment.

The imposition of this distance constraint defines the allowable number of inter-industry transfers, therefore reducing the number of decision variables to be considered.

The form of the cost functions applicable to the specific area of interest also is of considerable importance. In the unlikely event that all functions can be assumed to be linear, the problem is reduced to an easily solvable linear program, thereby requiring smaller amounts of computer time and allowing for the easy evaluation of confidence levels. The functions associated with wastewater treatment and conveyance usually are assumed to be non-linear, concave power functions, which introduce the non-linear difficulties and the associated problems of minimization of concave functions which were specifically considered in this study. If these functions can be assumed to be exponential, or linear on semi-log paper, the concavity problem is reduced and the program can be solved using more conventional non-linear techniques, such as those developed by Himmelblau (35). The cost function associated with fresh water usually is a step function, as presented in Figure 3.2, with unit cost decreasing as the amount of water used increases. This function can reasonably be assumed to be stepwise linear, and easily incorporated into the cost function. It is also possible to make an exponential approximation to the function, and more non-linearities are introduced into the problem. Other types of pricing structures can be considered, such as the fixed rate for industrial users which was used in the evaluation of Policy II, or an increasing unit cost with an increase in water usage.

SOLUTION TECHNIQUE

The algorithm used for solving the non-linear program is a search algorithm which inspects the vertices of the constraint polyhedron until an optimum is obtained. The use of this procedure guarantees that once the search stops, this optimum will be the global optimum, as opposed to a local optimum obtainable by other methods, such as linear approximation. The use of the linear approximation method, as described by Himmelblau (35), on the problem considered in this study was moderately successful. It was possible to reach a minimum in considerably less time than with the non-linear algorithm, but this minimum was only a local minimum. At this point the value of the objective function was very close to the value at the global optimum, but the values of the decision variables were very different at both points. Therefore, if the interest is in the value of the objective function and not in the value of the decision variables, linear approximation can be used as a quick, relatively accurate alternative algorithm. It also can be used to check results obtained by the concave non-linear programming algorithm.

LIMITATIONS OF THE MODEL

The use of this model is limited by computer time and not by storage. There is no way to predict beforehand what the Central Processing Unit (CPU) time will be for a specific problem, but the experience in this study indicates that ten to twelve water users could be handled in less than ten minutes CPU time. The biggest problem considered generated twenty-one constraints and forty variables. This program was solved in approximately seven CPU minutes, using a CDC 6600 computer. Memory requirements were approximately 100 K core units.

The size of the constraint matrix is determined by the number of users. For each user there are two constraints, one to guarantee that water "requirement" will be satisfied and a second for the mass balance on each user. In addition, there is another constraint for the total system when the amount of freshwater available is limited. The number of constraint equations for a specific problem is then 2 x (number of users) + 1. The number of variables cannot be determined beforehand, since they are dependent on the quality of the effluents and on the intake requirements. In general, the size of the constraint matrix grows fast as users are added. When saline water was considered as a cooling alternative, the constraints were increased from twenty-one to forty-one and the variables went from forty to ninety-four. After ten minutes of CPU time, the algirithm had made very little progress in moving toward the optimum. It was not possible to estimate what the required time for completion would be, but it was considered unacceptable.

The model has the capability of accepting additional linear constraints that can be used to eliminate specified transfers or to limit the amount of water that can be transferred from one user to another. However, it is not possible to introduce non-linear constraints and use the present algorithm. Non-linear constraints also would reduce the size of the problem that could be considered, since they would introduce more difficulties into the program.

POLICY SELECTION

Three different policies designed to reduce water demand were evaluated. These policies were selected among a considerable number of possibilities as being most likely to be implemented by decision-makers in the area, based on their ease of application and their use elsewhere. It is possible to use the model for the evaluation of other policies, subject to the limitations discussed above. Possibilities include the use of an increase in unit cost of fresh water with an increase in use and the use of flat rates for municipalities. It is also possible to consider effluent taxes in the form of power functions, but this introduces additional non-linearities and complicates the application of the solution algorithm.

Policies which increase the cost of fresh water tend to cause the higher reductions in demand, but at the same time are the more expensive. These policies eventually cause total reuse of wastewater, because all users, both municipal and industrial, have an economic incentive for reuse. Policies that selectively increase the cost of fresh water for specified sectors have a smaller economic effect on the system, but cause smaller reductions in demand and cannot be used if it is desired to totally eliminate the discharge of wastewater. The imposition of charges on the return flows causes a reduction in demand, but in order to make this reduction significant the charge must be applied to all users. Policies which combine an increase in fresh water cost with an effluent charge can be used also to accomplish zero discharge of wastewater.

CHAPTER 6
CONCLUSIONS

MODEL DEVELOPMENT

1. A non-linear regional water supply model that considers the difference between "requirement" and "demand" in forecasting future water needs was developed and solved by a search technique.

2. A non-linear algorithm was required to guarantee a global minimum. The linear approximation method provides a good estimate of the optimal value of the objective function. However, if the specific values of the decision variables are important, this approximation is inadequate.

3. This model can be expanded to include a larger number of users by developing a more efficient algorithm or by incorporating the information derived from the linear approximation method into the present algorithm.

4. This model provides to engineers and planners a methodology by which the technological and economic impacts of alternative water treatment, recycle, and pricing may be evaluated under various demographic and economic growth conditions.

MODEL APPLICATION

5. The application of the model to the Corpus Christi area in 1974 indicates that use of the available water resource was not optimal and a 10 percent reduction in demand was readily available by means of transfers between users.

6. A 40 percent reduction in demand can occur if the cost of fresh water is increased by a factor of 5.5 for all users. Wastewater discharged is reduced 80 percent.

7. A uniform increase in the cost of fresh water by a factor of 8.0 causes total recycle and zero discharge of wastewater.

8. Increasing the cost of fresh water only for industry to $1.75/1000 gallons causes a 30 percent reduction in demand and a 65 percent reduction in wastewater discharged. Zero discharge of wastewater is not achieved with higher costs of fresh water.

9. The imposition of an effluent charge of $1.25/1000 gallons of wastewater discharged to the industrial sector caused a 15 percent reduction in demand and a 35 percent reduction in wastewater discharged. Further increases in effluent charges do not cause any further reductions in demand.

10. The increased cost to the industries in the area resulting from the implementation of the three policies considered is 1 to 2 percent of the gross output.

11. The high total dissolved solids concentrations in the municipal return flows in the area is the most important constraint to water reuse.

APPENDIX I

PROGRAM LISTING

```
   2021.000                  10.000    200.000
INDUSTRY  1                75     5   629     0   7   13    9   4400   1   7   1.4    3.5
        .64      23.00         0.00    4820.00
INDUSTRY  2               300   300   650     0   7   33   23   3600   1   7   4.0    2.2
        .42      23.00         0.00    2370.00
CORPUS CHRISTI             15     2   500     1   7   12    9   2000   0   7   6.5-   1.1
        .35      19.00         0.00   31350.00
     .                                 .                           .
     .                                 .                           .
     .                                 .                           .
                     OTHER USERS
     .                                 .                           .
     .                                 .                           .
     .                                 .                           .
 RRRRRRRRRR
 BLANK CARD
   000
   123124000.000
   000
```

SAMPLE INPUT DATA

```
      PROGRAM [illegible](INPUT,TAPE1,TAPE2,OUTPUT)
      COMMON/A/B(47),A(47,147)
      COMMON/B/C(147)
      COMMON/C/INFLAG,MX,NN,KO(6),KB(147),P(147),JH(47),X(47),
     1Y(47),PE(147),E(22Ø9),FE(47,47),KEL,JJN(1ØØ),NNMX
      DIMENSION SNAME(2,24),QIN(5,24),QOUT(5,24),GELOC(2,24),
     1Q1(5),Q2(5),GE(2),G1(2),CC(23,23),KXX(147),RRKB(147)
      REAL L(24),K(24),PP(24),D(24),AA(23,23),BB(23,23),
     1RRKXX(147),U(147)
      INTEGER IB(23,23),NOROW(147),NOCOL(147),EXTRA(25)
      COMMON AA,BB,CC,NOROW,NOCOL,K,PP
      EQUIVALENCE(RRKB,KB)
      EQUIVALENCE (RKXX,KXX)
      EQUIVALENCE (ISIGN,SIGN)
      DO 54 J=1,23
      K(J)=PP(J)=NOROW(J)=NOCOL(J)=Ø
      DO 54 JJ=1,23
   54 AA(J,JJ)=BB(J,JJ)=CC(J,JJ)=Ø.Ø
      K(24)=PP(24)=Ø.Ø
C THE FIRST CARD IS AN OPTION CARD
C UPDATE=CURRENT FOR CONSTRUCTION COST INDEX
C INFO=PRINT OUT OPTIONS
C       =1 GIVES MINIMUM OUTPUT, JUST RESULTS
C       =2 ALSO PRINTS A, B, ^ C MATRICES
C       =3 ALSO PRINTS ALGORITHM INFORMATION
C       =4 STOPS PROGRAM BEFORE A,B,C ARE GENERATED
C TMAX=MAX COST ALLOWED, CENTS/1ØØØ GAL.
C DMAX=MAX DISTANCE FOR PIPING, MILES
      READ 84,UPDATE,INFO,DMAX,TMAX,IDZ
   84 FORMAT(F10.3,I10,2F10.3,I10)
      UPDATE=UPDATE/1942.
      INFLAG=Ø
      I=1
    3 READ 1,((SNAME(K1,I),K1=1,2),(QIN(K2,I),K2=1,5),
     1(QOUT(K3,I),K3=1,5),(GELOC(K4,I),K4=1,2))
      READ 2,L(I),K(I),PP(I),D(I)
      IF(L(I).EQ.1.0)L(I)=Ø.9999
      L(I)=L(I)*D(I)
      I=I+1
      IF(SNAME(1,I-1).NE.10HRRRRRRRRRR)GO TO 3
C LAST CARD MUST HAVE SNAME EQUAL TO RRRRRRRRRR
      I=I-2
    1 FORMAT(2A10,10F5.Ø,2F5.1)
    2 FORMAT(4F10.2)
C I INDICATES THE NUMBER OF SOURCES.SEQUE EVALUATES A ^ B FOR THE
C COST FUNCTION FOR THE IXI COMBINATIONS. PARAMETERS IN QIN ^ QOUT
C ARE BOD,SS,TDS,TOTAL COLIFORMS(TC),^PH, IN THAT ORDER.
      DO 4 J=1,I
      DO 8 JM=1,2
    8 G1(JM)=GELOC(JM,J)
      DO 4 JK=1,I
      DO 5 JM=1,5
    5 Q1(JM)=QOUT(JM,J)
      DO 6 JM=1,5
    6 Q2(JM)=QIN(JM,JK)
      DO 7 JM=1,2
    7 GE(JM)=GELOC(JM,JK)
C IT IS ASSUMED THAT THE FULL SEQUENCE WILL CLEAN ANYTHING
      DIST=SQRT((GE(1)-G1(1))**2+(GE(2)-G1(2))**2)
      IF(DIST.GE.DMAX)GO TO 4
      CALL SEQUE(Q2,Q1,A1,B1,UPDATE)
```

```
      IF(A1.GE.TMAX)GO TO 4
C AA(I,J) IS FROM J TO I
      AA(JK,J)=A1
      BB(JK,J)=B1
      CC(JK,J)=1.25*UPDATE*DIST
C CC CONTAINS THE INFORMATION FOR TRANSPORTATION COST EVALUATION
    4 CONTINUE
    9 FORMAT(49X,*WATER ALLOCATION MODEL*)
   1Ø FORMAT(//,15X,*FROM COST AND DISTANCE CONSIDERATIONS THE *,
     1*FOLLOWING ALTERNATIVES ARE CONSIDERED FEASIBLE:*)
   11 FORMAT(5X,*FROM*,21X,*TO*,15X,*TREATMENT COST EQUATION*,
     1* (CENTS/1ØØØ GAL)*,5X,*TRANSPORTATION COST*)
   12 FORMAT(5X,*MAXIMUM COST ALLOWED (CENTS/1ØØØ GAL):*,F6.1)
   13 FORMAT(5X,*MAXIMUM DISTANCE ALLOWED (MILES):*,F6.1)
   16 FORMAT(1X,2A1Ø)
   17 FORMAT(26X,2A1Ø,7X,F6.1,1ØH X FLOW**(,F6.3,1H),13X,F6.1,
     116H X FLOW**(-.5Ø5))
   19 FORMAT(*1*)
C ARE THERE ANY ALTERNATIVES WHICH MUST BE ZERO≥
      READ 2Ø,IP
      IF(IP.EQ.Ø)GO TO 21
      DO 22 JJ=1,IP
      READ 23,KN,KM
   22 AA(KN,KM)=BB(KN,KM)=CC(KN,KM)=Ø.Ø
   2Ø FORMAT(I5)
   23 FORMAT(2I5)
   21 CONTINUE
      PRINT 19
      PRINT 9
      PRINT 1Ø
      PRINT 11
      NN9=Ø
C COUNT THE NUMBER OF VARIABLES FOR THE LP AND PRINT THE
C ONES THAT ARE NOT ZERO
      DO 14 J=1,I
      IK=Ø
      DO 15 JJ=1,I
      IF(BB(JJ,J).NE.Ø.Ø)NN9=NN9+1
   15 IF(BB(JJ,J).NE.Ø.Ø)IK=1
      IF(IK.EQ.1)PRINT 16,SNAME(1,J),SNAME(2,J)
      DO 18 JJ=1,I
   18 IF(BB(JJ,J).NE.Ø.Ø)PRINT 17,SNAME(1,JJ),SNAME(2,JJ),AA(JJ,J),
     1BB(JJ,J),CC(JJ,J)
   14 CONTINUE
C NUMBER OF X≠S IS NXS
      NXS=NN9
      PRINT 12,TMAX
      PRINT 13,DMAX
      PRINT 19
      PRINT 24
   24 FORMAT(5X,*CONDITIONS USED AS INPUT FOR THE LP*)
C NUMBER OF VARIABLES(TOTAL)
C COMPOSED OF I Q≠S, I EFFLUENT, AND NXS X≠S
      NN9=NN9+I+I
      PRINT 25,NN9,NXS,I,I
   25 FORMAT(1ØX,*NUMBER OF VARIABLES:*,I5,/,15X,*COMPOSED OF*,
     1I4,* X≠S,*,I4,* Q≠S,AND*,I4,* EFFLUENT*)
      MX9=I*2
      PRINT 26,MX9
   26 FORMAT(1ØX,*NUMBER OF CONSTRAINTS:*,I4)
      MX=MX9
      NN=NN9
```

```
      PRINT 69,MX,NN
   69 FORMAT(10X,*THE TOTAL NUMBER OF CONSTRAINTS IS THEN EQUAL TO *,
     1I4,/,10X,*THE TOTAL NUMBER OF VARIABLES IS THEN *,I4)
C ADDITION OF UPPER LIMIT ON SUM OF Q*S
      READ 94,IUP,QMAX
   94 FORMAT(I5,F10.3)
      IF(IUP.EQ.0)GO TO 91
      B(MX+1)=QMAX
      A(MX+1,NN+1)=1.0
      DO 92 J=1,I
   92 A(MX+1,NXS+J)=1.0
      MX=MX+1
      NN=NN+1
      PRINT 93
   93 FORMAT(10X,*AN UPPER LIMIT ON THE SUM OF Q*S EXISTS,THEREFORE*)
      PRINT 69,MX,NN
   91 CONTINUE
      KOU=0
   87 FORMAT(2F10.0,I10,25I2)
C ADD CONSTRAINTS, IF DESIRED
C IIK=NO. OF NEW CONSTRAINT ROWS
C SIGN=-1 IF CONSTRAINT IS GT, =+1 IF LT, AND =0 IF EQ
C QMAX IS THE RHS, JJ1 IS THE NO. OF VARIABLES AFFECTED AND EXTRA
C WHICH ONES(UP TO 25)
      READ 20,IIK
      IF(IIK.EQ.0)GO TO 85
      DO 86 J=1,IIK
      READ 87,SIGN,QMAX,JJ1,(EXTRA(JJ),JJ=1,JJ1)
      B(MX+J)=QMAX
      DO 88 JZ=1,JJ1
      K7=EXTRA(JZ)
   88 A(MX+J,K7)=1.0
      IF(ISIGN.EQ.0)GO TO 89
      KOU=KOU+1
      A(MX+J,NN+KOU)=SIGN
   89 CONTINUE
   86 CONTINUE
      MX=MX+IIK
      NN=NN+KOU
      PRINT 90
   90 FORMAT(10X,*SOME MORE CONSTRAINTS HAVE BEEN ADDED,THEREFORE*)
      PRINT 69,MX,NN
   85 CONTINUE
      IF(INFO.EQ.4)STOP
   95 CONTINUE
C VARIABLES WILL BE ORDERED AS:X, Q, AND EFFLUENT
C IB WILL KEEP TRACK OF WHICH VARIABLE IS WHICH FOR NON-SLACK
C IB HAS DIMENSIONS OF IXI
      IH=0
      DO 33 J=1,I
      DO 33 JJ=1,I
      IF(BB(J,JJ).EQ.0.0)GO TO 33
      IH=IH+1
      IB(J,JJ)=IH
   33 CONTINUE
      DO 104 J=1,I
      DO 104 JJ=1,I
      KJZZ=IB(J,JJ)
  104 IF(KJZZ.NE.0)D(KJZZ)=D(JJ)
C FOR THE X VARIABLES: NOROW(I) HAS THE ROW NUMBER OF THE
C ITH. VARIABLE IN THE AA,BB AND CC MATRICES. NOCOL(I) IS
C THE SAME FOR THE COLUMN NUMBER.
```

```
      DO 52 J=1,I
      DO 52 JJ=1,I
      K1=IB(J,JJ)
      IF(K1.EQ.0)GO TO 52
      NOROW(K1)=J
      NOCOL(K1)=JJ
   52 CONTINUE
C*****************************************************************
C GENERATION OF CONSTRAINTS MATRIX FOLLOWS
C*****************************************************************
C GREATER THAN(MASS BALANCES) GO FIRST THEN EQUALITIES
      DO 27 J=1,I
      DO 28 JJ=1,I
      IF(J.EQ.JJ)GO TO 28
      KA=IB(J,JJ)
      IF(IB(J,JJ).NE.0)A(J,KA)=1.0
      K1=IB(JJ,J)
      IF(IB(JJ,J).NE.0)A(J,K1)=-1.0
   28 CONTINUE
      A(J,NXS+J)=1.0
   27 A(J,NXS+I+J)=-1.0
C EQUALITY CONSTRAINTS(DEMAND FULFILLMENT)
      KJK=0
      DO 29 J=1,I
      DO 30 JJ=1,I
      IF(BB(J,JJ).EQ.0.0)GO TO 30
      KJK=KJK+1
      A(J+I,KJK)=1.0
   30 CONTINUE
      A(J+I,NXS+J)=1.0
   29 CONTINUE
C PRINT OUT A(I,J) MATRIX, IF DESIRED
      IF(INFO.LT.2)GO TO 37
      J=1
   31 JJ=J+19
      IF(JJ.GE.NN)JJ=NN
      PRINT 32,J,JJ
   32 FORMAT(*1*,40X,*THE CONSTRAINTS MATRIX, COLUMNS *,I4,* TO *,I4)
      PRINT 34,(KR,KR=J,JJ)
   34 FORMAT(//,10X,20I4,/)
      DO 36 JR=1,MX
   36 PRINT 35,JR,(A(JR,JM),JM=J,JJ)
   35 FORMAT(I5,5X,20F4.0)
      J=J+20
      IF(J.GT.NN)GO TO 37
      GO TO 31
   37 CONTINUE
C*****************************************************************
C GENERATE THE RHS VECTOR
C*****************************************************************
      DO 38 J=1,I
   38 B(J)=L(J)
      JK=I+1
      DO 39 J=JK,MX9
   39 B(J)=D(J-I)
C PRINT OUT B VECTOR, IF DESIRED
      IF(INFO.LT.2)GO TO 79
      PRINT 40
   40 FORMAT(*1*,40X,*THE RHS VECTOR B(I)*,//)
      PRINT 41,(J,B(J),J=1,MX)
   41 FORMAT(10X,5(2X,*B(*,I4,*)=*,F10.3))
   79 CONTINUE
```

```
C MAKE APPROXIMATION OF C TO GET UPPER BOUND
      DO 142 J=1,NXS
      DO 143 JJ=1,I
      DO 143 JK=1,I
      IF(IB(JJ,JK).NE.J)GO TO 143
      C(J)=AA(JJ,JK)+CC(JJ,JK)
  143 CONTINUE
  142 CONTINUE
      JK=NXS+1
      JJ=NXS+I
      DO 144 J=JK,JJ
  144 C(J)=K(J-NXS)
      JK=NXS+I+1
      JJ=NXS+I+I
      DO 145 J=JK,JJ
  145 C(J)=PP(J-NXS-I)
      CALL SIMPLE
      IF(KO(1).NE.0)PRINT 83,KO(1)
      CALL COST2(RRKB,TC,NXS,I)
      FU=TC
      TC=TC/100.
C SAVE FIRST POINT, X0
C KXX IS THE CURRENT BEST SOLUTION
      DO 55 J=1,NN9
   55 KXX(J)=KB(J)
C****************************************************************
C CONSTRUCTION OF P2
C****************************************************************
C   FOR THE X*S
      DO 43 JJ=1,I
      DO 43 JK=1,I
      J=IB(JJ,JK)
      IF(J.EQ.0)GO TO 43
      C(J)=AA(JJ,JK)/(U(J)**(1.-BB(JJ,JK)))
      C(J)=C(J)+CC(JJ,JK)/U(J)**1.505
   43 CONTINUE
C   FOR THE Q*S
      JK=NXS+1
      JJ=NXS+I
      DO 44 J=JK,JJ
   44 C(J)=K(J-NXS)
C FOR THE EFFLUENT
      JK=NXS+I+1
      JJ=NXS+I+I
      DO 45 J=JK,JJ
   45 C(J)=PP(J-NXS-I)
C PRINT FIRST GUESS FOR C(I), IF DESIRED
      IF(INFO.LT.2)GO TO 80
      PRINT 46
   46 FORMAT(*1*,40X,*THE VALUE OF C(I) FOR P2*,//)
      PRINT 47,(J,C(J),J=1,NN9)
   47 FORMAT(10X,5(2X,*C(*,I4,*)=*,F10.3))
   80 CONTINUE
C START ALGORITHM
      FIRST=-10.
C OBTAIN INITIAL POINT X0
      CALL SIMPLE
      J1=0
      DO 111 J=1,NN
      DO 110 JJ=1,MX
  110 IF(J.EQ.JH(JJ)) GO TO 111
      J1=J1+1
```

```
      JJN(J1)=J
  111 CONTINUE
      DO 107 J=1,MX
      DO 107 J1=1,MX
  107 EE(J,J1)=E(J+MX*(J1-1))
C CHECK FOR PROBLEM FEASIBILITY
      IF(KO(1).NE.0)PRINT 83,KO(1)
   83 FORMAT(//,*XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX*,*  PROBLEM IS *,
     1*NOT FEASIBLE,KO(1) IS=*,I3,*XXXXXXXXXXXXXXXXXXXXXXXXXXX*)
      IF(KO(1).NE.0)STOP
C EVALUATE COST FOR INITIAL POINT, THAT IS, FIND UPPER LIMIT F(X0)=FU
C  STEP 2
C FIND LOWER LIMIT, THAT IS, G(XO)=FL  (STEP 1)
      FL=0.0
      DO 97 J=1,NN9
   97 FL=FL+C(J)*RRKB(J)
      IF(INFO.LT.3)GO TO 78
      PRINT 19
      PRINT 48
   48 FORMAT(20X,*THE INITIAL VALUE OF X(I) FROM P2*)
      PRINT 51
      IF(KO(1).EQ.0)PRINT 50
   49 FORMAT(10X,5(2X,*X(*,I4,*)=*,F10.3))
   50 FORMAT(10X,*THE SOLUTION IS OPTIMAL FOR THIS DUMMY RUN*)
   51 FORMAT(//)
      PRINT 49,(J,KB(J),J=1,NN)
      TC=FL/100.
      PRINT 53,TC
   53 FORMAT(//,20X,*TOTAL COST FOR THIS SYSTEM IS(DOLLARS)*,F14.2)
   78 CONTINUE
   82 CONTINUE
C *************STEP 3
C USE MURTYS METHOD TO FIND NEXT BEST EXTREME POINT
C**************************MURTYS THING*****************
      CALL MURTY(FL,XMIN,FIRST)
      FIRST=100.
C KB CONTAINS THE NEXT BEST POINT, XK
C STEP 3A
C FIND G(XK)
      G=XMIN
      IF(G.LT.(FU-0.001))GO TO 56
C THIS BRANCH ENDS THE LOOP
      GO TO 76
   56 CONTINUE
C STEP 3B
      FL=G
C ***********STEP 4
      CALL COST2(RRKB,TC,NXS,I)
      IF(TC.GE.FU)GO TO 82
      FU=TC
C REPLACE CURRENT BEST SOLUTION
      DO 57 J=1,NN9
   57 KXX(J)=KB(J)
      GO TO 82
   76 CONTINUE
      TC=FU/100.
C PRINT LP INFORMATION
      PRINT 99,(KO(J),J=2,5)
   99 FORMAT(5X,*NO. OF ITERATIONS *,I5,/,5X,*NO. OF PIVOTS SINCE *,
     1*LAST INVERSION *,I5,/,5X,*NO. OF INVERSIONS *,I5,/,5X,
     2*TOTAL NO. OF PIVOTS *,I5)
C PRINT RESULTS
```

```
      PRINT 19
      PRINT 9
      PRINT 61
   61 FORMAT(//,56X,*RESULTS*,//,10X,*USER TO USER WATER REUSE*)
      PRINT 62
   62 FORMAT(5X,*FROM*,26X,*TO*,22X,*AMOUNT OF WATER(1000 GAL)*)
      DO 63 J=1,NXS
      IF(RKXX(J).LE.1.5)GO TO 63
      K11=NOROW(J)
      K12=NOCOL(J)
      PRINT 64,SNAME(1,K12),SNAME(2,K12),SNAME(1,K11),SNAME(2,K11),
     1KXX(J)
   63 CONTINUE
   64 FORMAT(5X,2A10,10X,2A10,11X,F6.0)
      PRINT 19
      PRINT 9
      PRINT 65
   65 FORMAT(//,56X,*RESULTS*,//)
      PRINT 66
   66 FORMAT(10X,*USER*,20X,*WATER INTAKE(1000 GAL)*,20X,
     1*EFFLUENT(1000 GAL)*)
      K11=NXS+1
      K12=NXS+I
      DO 67 J=K11,K12
      JRS=J-NXS
      JSR=J+I
      PRINT 68,SNAME(1,JRS),SNAME(2,JRS),KXX(J),KXX(JSR)
   67 CONTINUE
   68 FORMAT(5X,2A10,14X,F6.0,35X,F6.0)
      PRINT 53,TC
      STOP
      END
      SUBROUTINE SEQUF(QIN,QOUT,A,B,UPDATE)
      DIMENSION QIN(5),QOUT(5),BOD(7),SS(7),TDS(7),ALT(2,7),ALT2(2,5),
     1ALT1(2,4)
      REAL CL2(2,7),NEU(2,7)
C TREATMENT SEQUENCE IS: PRELIMINARY,CLARIFICATION,ACTIVATED SLUDGE,
C COAGULATION,FILTERS,CARBON ADSORPTION,ION EXCHANGE AND CHLORINATION
C OR NEUTRALIZATION AS REQUIRED
      DATA BOD/0.0,0.4,0.9,0.83,0.6,0.8,0.97/,SS/0.1,0.75,0.6,0.7,
     10.85,0.85,0.97/,TDS/0.0,0.1,0.3,0.2,0.0,0.0,0.97/
      DATA (ALT(I),I=1,14)/.54,-.45,22.2,-.243,36.7,-.242,
     144.2,-.195,58.7,-.226,91.5,-.253,176.5,-.22/
      DATA (CL2(I),I=1,14)/2.77,-.184,24.47,-.233,38.97,-.236,
     146.41,-.193,60.91,-.223,93.71,-.249,178.71,-.219/
      DATA (NEU(I),I=1,14)/4.82,-.432,26.52,-.264,41.02,-.256,
     148.46,-.208,62.96,-.235,95.76,-.258,180.76,-.223/
      DATA (ALT1(I),I=1,8)/7.44,-.05,21.9,-.202,54.7,-.26,139.7,-.215/
      DATA (ALT2(I),I=1,10)/14.5,-.241,21.9,-.156,36.4,-.216,69.2,
     1-.256,154.4,-.217/
      DO 1 J=1,5
    1 IF(QOUT(J).GT.QIN(J))GO TO 2
      IF(QOUT(4).GE.QIN(4))GO TO 4
      A=UPDATE*2.23
      B=-0.15
      RETURN
    4 IF(QOUT(5).GE.QIN(5))GO TO 5
      A=UPDATE*4.28
      B=-0.43
      RETURN
    5 A=0.0
      B=1.0
```

```
      RETURN
    2 IF(QOUT(1).LE.100.0)GO TO 9
      IF(QOUT(2).LE.100.0)GO TO 10
      DO 3 J=1,7
      QOUT(1)=QOUT(1)*(1.-BOD(J))
      QOUT(2)=QOUT(2)*(1.-SS(J))
      QOUT(3)=QOUT(3)*(1.-TDS(J))
      DO 6 JJ=1,3
    6 IF(QOUT(JJ).GT.QIN(JJ))GO TO 3
      GO TO 7
    3 CONTINUE
    7 A=ALT(1,J)*UPDATE
      B=ALT(2,J)
      IF(QOUT(4).GE.QIN(4))GO TO 8
      A=CL2(1,J)*UPDATE
      B=CL2(2,J)
      RETURN
    8 IF(QOUT(5).GE.QIN(5))RETURN
      A=NEU(1,J)*UPDATE
      B=NEU(2,J)
      RETURN
    9 DO 11 J=1,4
      QOUT(1)=QOUT(1)*(1.-BOD(J+3))
      QOUT(2)=QOUT(2)*(1.-SS(J+3))
      QOUT(3)=QOUT(3)*(1.-TDS(J+3))
      DO 12 JJ=1,3
   12 IF(QOUT(JJ).GT.QIN(JJ))GO TO 11
      GO TO 13
   11 CONTINUE
   13 A=ALT1(1,J)*UPDATE
      B=ALT1(2,J)
      RETURN
   10 DO 14 J=1,5
      QOUT(1)=QOUT(1)*(1.-BOD(J+2))
      QOUT(2)=QOUT(2)*(1.-SS(J+2))
      QOUT(3)=QOUT(3)*(1.-TDS(J+2))
      DO 15 JJ=1,3
   15 IF(QOUT(JJ).GT.QIN(JJ))GO TO 14
      GO TO 16
   14 CONTINUE
   16 A=ALT2(1,J)*UPDATE
      B=ALT2(2,J)
      RETURN
      END
      SUBROUTINE SIMPLE
      COMMON/A/B(47),A(47,147)
      COMMON/B/C(147)
      COMMON/C/INFLAG,MX,NN,KO(6),KB(147),P(147),JH(47),X(47),
     1Y(47),PE(147),E(2209),EE(47,47),KEL,JJN(100),NNMX
      DIMENSION RRKB(147)
      EQUIVALENCE (XX,LL)
      EQUIVALENCE(RRKB,KB)
      LOGICAL FEAS, VER, NEG, TRIG, KQ, ABSC
C         SET INITIAL VALUES, SET CONSTANT VALUES
      ITER = 0
      NUMVR = 0
      NUMPV = 0
      M=MX
      N=NN
      TEXP  =   .5**16
      NCUT=10*M+10
      NVER  =   M/2  +  5
```

```
      M2 = M**2
      FEAS = .FALSE.
      IF  (INFLAG.NE.0)  GO TO 1400
C* ≠NEW≠    START  PHASE ONE WITH SINGLETON BASIS
      DO 1402  J = 1,N
        KB(J) = 0
        KQ = .FALSE.
        DO 1403  I = 1,M
          IF (A(I,J).EQ.0.0)  GO TO 1403
          IF (KQ.OR.A(I,J).LT.0.0) GO TO 1402
          KQ = .TRUE.
 1403   CONTINUE
        KB(J) = 1
 1402 CONTINUE
 1400 DO 1401  I = 1,M
        JH (I) = -1
 1401 CONTINUE
C* ≠VER≠    CREATE INVERSE FROM ≠KB≠ AND ≠JH≠     (STEP 7)
 1320 VER = .TRUE.
      INVC = 0
      NUMVR   =   NUMVR  +1
      TRIG = .FALSE.
      DO 1101 I=1,M2
        E(I) = 0.0
 1101 CONTINUE
      MM=1
      DO 1113  I = 1,M
        E(MM) = 1.0
        PE(I)   =   0.0
        X(I) =   B(I)
        IF (JH(I) .NE.0) JH(I) = -1
        MM = MM + M + 1
 1113 CONTINUE
C                 FORM INVERSE
      DO 1102  JT = 1,N
        IF (KB(JT).EQ.0)  GO TO 1102
        GO TO 600
C 600   CALL JMY
C                        CHOOSE PIVOT
 1114   TY = 0.0
        KQ = .FALSE.
        DO 1104 I = 1,M
          IF (JH(I).NE.-1.OR.ABS(Y(I)).LE.TPIV)  GO TO 1104
          IF (KQ) GO TO 1116
          IF (X(I).EQ.0.)  GO TO 1115
          IF (ABS(Y(I)/X(I)).LE.TY)  GO TO 1104
          TY = ABS(Y(I)/X(I))
          GO TO 1118
 1115     KQ = .TRUE.
          GO TO 1117
 1116     IF (X(I).NE.0..OR.ABS(Y(I)).LE.TY)  GO TO 1104
 1117     TY = ABS(Y(I))
 1118     IR = I
 1104   CONTINUE
        KB(JT) = 0
C                        TEST PIVOT
        IF (TY.LE.0.)    GO TO 1102
C                        PIVOT
        GO TO 900
C 900   CALL PIV
 1102 CONTINUE
C                 RESET ARTIFICIALS
```

```
      DO 1109  I = 1,M
        IF (JH(I).EQ.-1)  JH(I) = 0
        IF (JH(I).EQ.0)  FEAS = .FALSE.
 1109 CONTINUE
 1200 VER = .FALSE.
C             ***           PERFORM ONE ITERATION          ***
C* ≠XCK≠    DETERMINE FEASIBILITY                     (STEP 1)
      NEG = .FALSE.
      IF (FEAS)  GO TO 500
      FEAS= .TRUE.
      DO 1201  I = 1,M
        IF (X(I).LT.0.0)  GO TO 1250
        IF (JH(I).EQ.0)  FEAS = .FALSE.
 1201 CONTINUE
C* ≠GET≠    GET APPLICABLE PRICES                     (STEP 2)
      IF (.NOT.FEAS)  GO TO 501
  500 DO 503 I = 1,M
        P(I) = PE(I)
        IF (X(I).LT.0.)  X(I) = 0.
  503 CONTINUE
      ABSC = .FALSE.
      GO TO 599
 1250 FEAS = .FALSE.
      NEG  = .TRUE.
  501 DO 504  J = 1, M
        P(J) = 0.
  504 CONTINUE
      ABSC = .TRUE.
      DO 505  I = 1,M
        MM = I
        IF (X(I).GE.0.0)  GO TO 507
        ABSC = .FALSE.
        DO 508 J = 1,M
          P(J) = P(J) + E(MM)
          MM = MM + M
  508   CONTINUE
        GO TO 505
  507   IF (JH(I).NE.0) GO TO 505
        IF (X(I).NE.0.) ABSC = .FALSE.
        DO 510  J = 1,M
          P(J) = P(J) - E(MM)
          MM = MM + M
  510   CONTINUE
  505 CONTINUE
C* ≠MIN≠    FIND MINIMUM REDUCED COST                 (STEP 3)
  599 JT = 0
      BB  =  0.0
      DO 701  J =1,N
        IF (KB(J).NE.0)   GO TO 701
        DT = 0.0
        DO 303 I = 1,M
          DT = DT + P(I) * A(I,J)
  303   CONTINUE
        IF (FEAS)  DT = DT + C(J)
        IF  (ABSC)  DT = - ABS(DT)
        IF (DT.GE.BB)  GO TO 701
        BB = DT
        JT = J
  701 CONTINUE
C  TEST FOR NO PIVOT COLUMN
      IF (JT.LE.0)  GO TO 203
C  TEST FOR ITERATION LIMIT EXCEEDED
```

```
      IF (ITER.GE.NCUT)  GO TO 160
      ITER = ITER +1
C* *JMY*    MULTIPLY INVERSE TIMES A(.,JT)          (STEP 4)
  600 DO 610  I= 1,M
        Y(I) = 0.0
  610 CONTINUE
      LL = 0
      COST = C(JT)
      DO 605   I= 1,M
        AIJT = A(I,JT)
        IF (AIJT.EQ.0.) GO TO 602
        COST = COST + AIJT * PE(I)
        DO  606  J = 1,M
          LL = LL + 1
          Y(J) = Y(J) + AIJT * E(LL)
  606   CONTINUE
        GO TO 605
  602   LL = LL + M
  605 CONTINUE
C         COMPUTE PIVOT TOLERANCE
      YMAX = 0.0
      DO 620  I  =  1,M
        YMAX = AMAX1( ABS(Y(I)),YMAX )
  620 CONTINUE
      TPIV  =  YMAX * TEXP
C            RETURN TO INVERSION ROUTINE, IF INVERTING
      IF (VER)  GO TO 1114
C        COST TOLERANCE CONTROL
      RCOST = YMAX/BB
      IF (TRIG.AND.BB.GE.-TPIV)  GO TO 203
      TRIG = .FALSE.
      IF (BB.GE.-TPIV)  TRIG = .TRUE.
C* *ROW*    SELECT PIVOT ROW                         (STEP 5)
C AMONG EQS. WITH X=0, FIND MAXIMUM Y  AMONG ARTIFICIALS, OR, IF NONE,
C  GET MAX POSITIVE Y(I) AMONG REALS.
      IR = 0
      AA = 0.0
      KQ = .FALSE.
      DO  1050  I =1,M
        IF (X(I).NE.0.0.OR.Y(I).LE.TPIV)  GO TO 1050
        IF (JH(I).EQ.0)  GO TO 1044
        IF (KQ) GO TO 1050
 1045   IF (Y(I).LE.AA)  GO TO 1050
        GO TO 1047
 1044   IF (KQ) GO TO 1045
        KQ = .TRUE.
 1047   AA = Y(I)
        IR = I
 1050 CONTINUE
      IF (IR.NE.0)  GO TO 1099
      AA = 1.0E+20
C              FIND MIN. PIVOT AMONG POSITIVE EQUATIONS
      DO 1010  I  = 1,M
        IF (Y(I).LE.TPIV.OR.X(I).LE.0.0.OR.Y(I)*AA.LE.X(I) ) GO TO 1010
        AA = X(I)/Y(I)
        IR = I
 1010 CONTINUE
      IF (.NOT.NEG)  GO TO 1099
C  FIND PIVOT AMONG NEGATIVE EQUATIONS, IN WHICH X/Y IS LESS THAN THE
C MINIMUM X/Y IN THE POSITIVE EQUATIONS, THAT HAS THE LARGEST ABSF(Y)
      BB = - TPIV
      DO 1030  I = 1,M
```

```
          IF (X(I).GE.0..OR.Y(I).GE.BB.OR.Y(I)*AA.GT.X(I) )  GO TO 1030
          BB = Y(I)
          IR = I
 1030 CONTINUE
C  TEST FOR NO PIVOT ROW
 1099 IF  (IR.LE.0)  GO TO 207
C* *PIV*     PIVOT ON (IR,JT)                          (STEP 6)
      IA = JH(IR)
      IF (IA.GT.0)  KB(IA) = 0
  900 NUMPV  =  NUMPV  +  1
      JH(IR) = JT
      KB(JT) = IR
      YI = -Y(IR)
      Y(IR) = -1.0
      LL = 0
C                             TRANSFORM INVERSE
      DO  904  J = 1,M
        L = LL + IR
        IF (E(L).NE.0.0)  GO TO 905
        LL = LL + M
        GO TO 904
  905   XY = E(L) / YI
        PE(J) = PE(J) + COST * XY
        E(L) = 0.0
        DO 906  I = 1,M
          LL  =  LL + 1
          E(LL) = E(LL)  + XY * Y(I)
  906   CONTINUE
  904 CONTINUE
C                             TRANSFORM X
      XY  =  X(IR) / YI
      DO 908  I  = 1, M
        XOLD = X(I)
        X(I) = XOLD + XY * Y(I)
        IF (.NOT.VER.AND.X(I).LT.0..AND.XOLD.GE.0.)  X(I) = 0.
  908 CONTINUE
      Y(IR) = -YI
      X(IR) = -XY
      IF (VER) GO TO 1102
      IF (NUMPV.LE.M) GO TO 1200
C  TEST FOR INVERSION ON THIS ITERATION
      INVC   = INVC   +1
      IF  (INVC.EQ.NVER)   GO TO 1320
      GO  TO  1200
C*  END OF ALGORITHM, SET EXIT VALUES                ***
  207 IF (.NOT.FEAS.OR.RCOST.LE.-1000.)  GO TO 203
C            INFINITE SOLUTION
      K  =  2
      GO TO 250
C          PROBLEM IS CYCLING
  160 K  =  4
      GO TO 250
C          FEASIBLE OR INFEASIBLE SOLUTION
203   K= 0
  250 IF (.NOT.FEAS)  K = K + 1
      DO 1399  J = 1,N
        XX  =  0.0
        KBJ  =  KB(J)
        IF (KBJ.NE.0)  XX = X(KBJ)
        KB(J) = LL
 1399 CONTINUE
      KO(1) = K
```

```
      KO(2) = ITER
      KO(3) = INVC
      KO(4) = NUMVR
      KO(5) = NUMPV
      KO(6) = JT
      RETURN
      END
      SUBROUTINE COST2(ST,T1,NE,KJ)
      DIMENSION ST(147),NOROW(147),NOCOL(147),AA(23,23),BB(23,23),
     1CC(23,23),K(24),PP(24)
      REAL K,PP
      COMMON AA,BB,CC,NOROW,NOCOL,K,PP
C ST IS NO. OF GALLONS GOING TO EACH PLACE, NE IS NO. OF X*S(NXS IN MAIN
C T1 IS THE TOTAL COST AND KJ IS I IN MAIN
      T1=0.0
      DO 1 I=1,NE
      IF(ST(I).EQ.0.0)GO TO 1
      K1=NOROW(I)
      K2=NOCOL(I)
      T1=T1+(AA(K1,K2)*(ST(I)/1000.)**BB(K1,K2)+CC(K1,K2)*(ST(I)/1000.)*
     1*(-.505))*ST(I)
    1 CONTINUE
      K3=NE+1
      K4=NE+KJ
      K5=K4+1
      K6=K4+KJ
      DO 2 I=K3,K4
    2 T1=T1+ST(I)*K(I-NE)
      DO 3 I=K5,K6
    3 T1=T1+ST(I)*PP(I-K4)
      RETURN
      END
      SUBROUTINE MURTY(ZOPT,XMIN,FIRST)
      COMMON/A/B(47),A(47,147)
      COMMON/B/C(147)
      COMMON/C/INFLAG,MX,NN,KO(6),KB(147),P(147),JH(47),X(47),
     1Y(47),PE(147),E(2209),EE(47,47),KEL,JJN(100),NNMX
      EQUIVALENCE(RRKB,KB)
      DIMENSION ARRAY1(10000),KOUNT2(1000),RKB(147),KOUNT(10000),
     1STORE(147),ALPHA(47),RRKB(147),ALPH(47)
C KOUNT KEEPS TRACK OF STARTING SECTOR IN STORAGE
C OF BASIC SEQUENCES IN ARRAY3
C KOUNT2 KEEPS TRACK OF STARTING SECTOR IN STORAGE OF BASE INVERSES
C IN TAPE2. II2 KEEPS TRACK OF THE ELEMENTS IN KOUNT2
C NU=NUMBER OF NON-ZERO ELEMENTS IN ARRAY1
C IF SECOND OR MORE CALL, GO TO 12
      IF(FIRST.GE.0.0)GO TO 12
      NNMX=NN-MX
      II1=0
      II2=1
      KEL=MX**2
   13 CONTINUE
C STORE BASE INVERSE AND ASSOCIATED JH AND JJN IN TAPE2
      KOUNT2(II2)=IOP(2HGP,2)
      CALL IOP(2HWB,2,JH,MX)
      CALL IOP(2HWB,2,JJN,NNMX)
      CALL IOP(2HWB,2,EE,KEL)
      CALL IOP(2HWR,2)
C FIND ADJACENT POINTS AND Z(TJ)
      SEC=-100.
      DO 4 J=1,MX
      JT=JH(J)
```

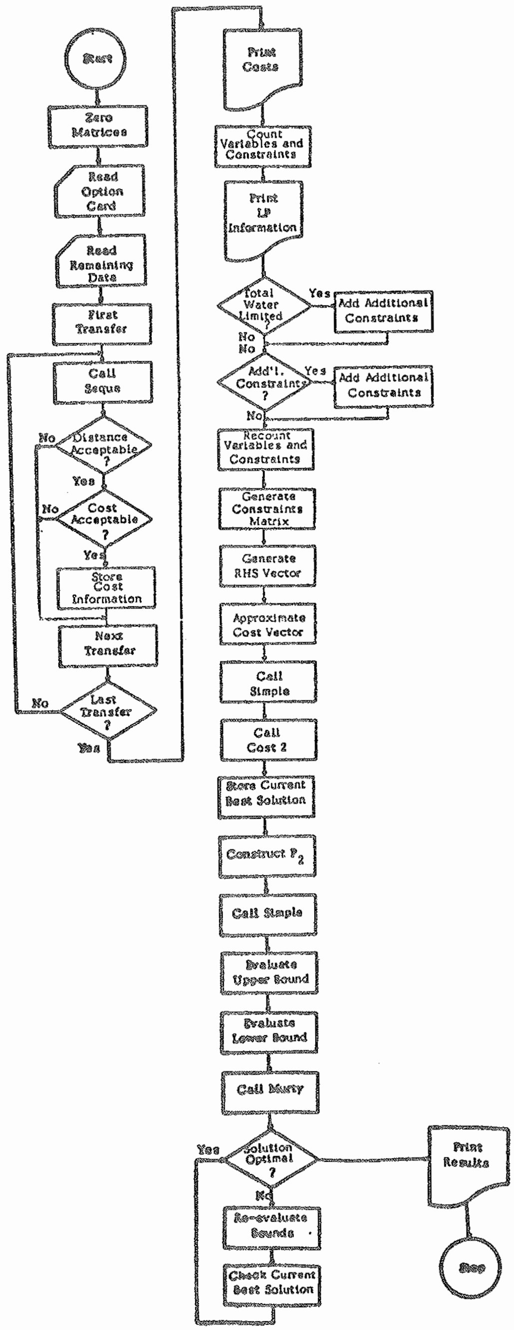
```
      DO 4 JJJ=1,NNMX
      JJ=JJN(JJJ)
C PIVOT
C CALCULATE ALPHA FOR ENTERING VARIABLE JJ
C DIMENSION OF ALPHA IS MX
      DO 3 J1=1,MX
      ALPHA(J1)=0.0
      DO 3 J2=1,MX
    3 ALPHA(J1)=ALPHA(J1)+EE(J1,J2)*A(J2,JJ)
C FIND THETA
      THETA=10000000000.
      DO 44 JS=1,MX
      JRD=JH(JS)
      IF(ALPHA(JS).LE.0.0)GO TO 44
      COEF=RRKB(JRD)/ALPHA(JS)
      IF(COEF.LE.THETA)THETA=COEF
   44 CONTINUE
C CALCULATE NEW X VECTOR RKB, AND FEASIBILITY AND Z
      Z=0.0
      DO 10 JS=1,MX
      JRD=JH(JS)
      IF(JRD.EQ.JT)GO TO 10
      RKB(JRD)=RRKB(JRD)-THETA*ALPHA(JS)
      IF(RKB(JRD).LT.0.01)GO TO 4
      Z=Z+RKB(JRD)*C(JRD)
   10 CONTINUE
      Z=Z+THETA*C(JJ)
      RKB(JJ)=THETA
      RKB(JT)=0.0
C IS Z ACCEPTABLE?(MAKING THE POINT ACCEPTABLE)
      IF(Z.LE.(ZOPT-0.0001))GO TO 4
      DO 19 M7=1,III
   19 IF(ABS(Z-ARRAY1(M7)).LE.1.00)GO TO 4
C STORE Z IN ARRAY1
      III=III+1
      ARRAY1(III)=Z
C STORE RKB IN ARRAY3
      IF(FIRST.GT.0.0)GO TO 18
      KOUNT(III)=IOP(2HGP,1)
   18 IF(SEC.GE.0.0.AND.FIRST.LT.0.0)GO TO 20
C IF FIRST NEW POINT, REPOSITION POINTER AS TO WRITE OVER LAST POINT
      CALL IOP(3HSPR,1,KOUNT(III))
   20 CALL IOP(2HWB,1,KOUNT2(II2),1)
      CALL IOP(2HWB,1,JJ,1)
      CALL IOP(2HWB,1,JT,1)
      CALL IOP(2HWB,1,ALPHA,MX)
      CALL IOP(2HWB,1,RKB,NN)
      CALL IOP(2HWR,1)
      SEC=10.
    4 CONTINUE
C FIND NEXT BEST BY SCANNING ARRAY1
   25 IN=1
      XMIN=1000000000000.
      DO 16 J=1,III
      IF(ARRAY1(J).GT.XMIN)GO TO 16
      IN=J
      XMIN=ARRAY1(J)
   16 CONTINUE
      ZOPT=XMIN
C GO TO ARRAY3 TO FIND BASIC SOLUTION CORRESPONDING TO IN
      CALL IOP(2HSP,1,KOUNT(IN))
      CALL IOP(2HRB,1,NOE,1)
```

```
      CALL IOP(2HRB,1,IIN,1)
      CALL IOP(2HRB,1,IOUT,1)
      CALL IOP(2HRB,1,ALPHA,MX)
      CALL IOP(2HRB,1,RKB,NN)
      DO 17 M3=1,NN
   17 RRKB(M3)=RKB(M3)
      III=III-1
      RETURN
   12 CONTINUE
C CHANGE E AND JH AND JJN
      CALL CHANGE(IIN,IOUT,NOE,ALPHA)
      II2=II2+1
C MOVE LAST POINT TO POSITION JUST VACATED IN ARRAY1 AND 3
C IN INDICATES POSITION JUST VACATED, III INDICATES LAST POINT
C MODIFY ARRAY1
      ARRAY1(IN)=ARRAY1(III+1)
C READ LAST POINT FROM ARRAY3
      CALL IOP(2HSP,1,KOUNT(III+1))
      CALL IOP(2HRB,1,IW,1)
      CALL IOP(2HRB,1,IY,1)
      CALL IOP(2HRB,1,IX,1)
      CALL IOP(2HRB,1,ALPH,MX)
      CALL IOP(2HRB,1,STORE,NN)
C REPOSITION POINTER AT IN AND WRITE LAST POINT HERE
      CALL IOP(3HSPR,1,KOUNT(IN))
      CALL IOP(2HWB,1,IW,1)
      CALL IOP(2HWB,1,IY,1)
      CALL IOP(2HWB,1,IX,1)
      CALL IOP(2HWB,1,ALPH,MX)
      CALL IOP(2HWB,1,STORE,NN)
      CALL IOP(2HWR,1)
      GO TO 13
      END
      SUBROUTINE CHANGE(IR,JT,NOE,ALPHA)
      COMMON/A/B(47),A(47,147)
      COMMON/B/C(147)
      COMMON/C/INFLAG,MX,NN,KO(6),KB(147),P(147),JH(47),X(47),
     1Y(47),PE(147),E(2209),EE(47,47),KEL,JJN(100),NNMX
      EQUIVALENCE(RRKB,KB)
      DIMENSION ALPHA(47),XI(47),D(47,47),CCC(47,47),RRKB(147)
C CHANGE E
C READ NEW E AND ASSOCIATED JH AND JJN
      CALL IOP(2HSP,2,NOE)
      CALL IOP(2HRB,2,JH,MX)
      CALL IOP(2HRB,2,JJN,NNMX)
      CALL IOP(2HRB,2,EE,KEL)
C REPOSITION POINTER AT END OF TAPE2,SO THAT THE NEW E CAN BE WRITTEN
C BY MORTY
      CALL IOP(3HSEI,2)
C CHANGE LIST OF BASIC VARIABLES IN JH AND EVALUATE XI
C CHANGE LIST OF NON-BASIC VARIABLES IN JJN
      DO 9 J=1,NNMX
    9 IF(JJN(J).EQ.IR)GO TO 10
   10 JJN(J)=JT
      DO 1 J=1,MX
    1 IF(JH(J).EQ.JT)GO TO 2
    2 JKEY=J
      JH(JKEY)=IR
      DIV=ALPHA(JKEY)
      DO 4 JJ=1,MX
    4 XI(JJ)=-ALPHA(JJ)/DIV
      XI(JKEY)=1./DIV
```

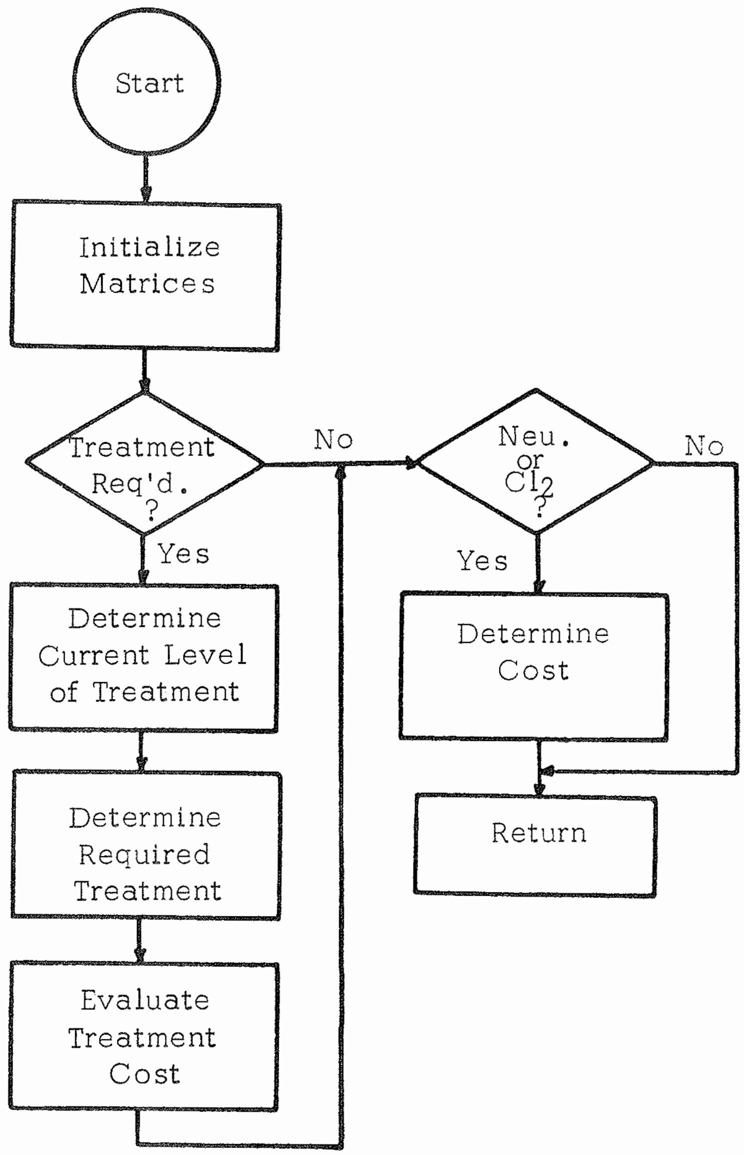
```
C FORM MULTIPLIER MATRIX D
      DO 6 J3=1,MX
      D(J3,J3)=1.0
    6 D(J3,JKEY)=XI(J3)
C OBTAIN NEW E BY MULT. OLD E X D
      DO 7 JK=1,MX
      DO 7 JM=1,MX
      CCC(JK,JM)=0.0
      DO 7 JN=1,MX
    7 CCC(JK,JM)=CCC(JK,JM)+D(JK,JN)*EE(JN,JM)
C MODIFY E AND REZERO D
      DO 8 JK=1,MX
      DO 8 JM=1,MX
      D(JK,JM)=0.0
    8 EE(JK,JM)=CCC(JK,JM)
      RETURN
      END

.................
..END-OF-RECORD..        1
.................


*****************
***END-OF-FILE***        1
*****************
```

APPENDIX II

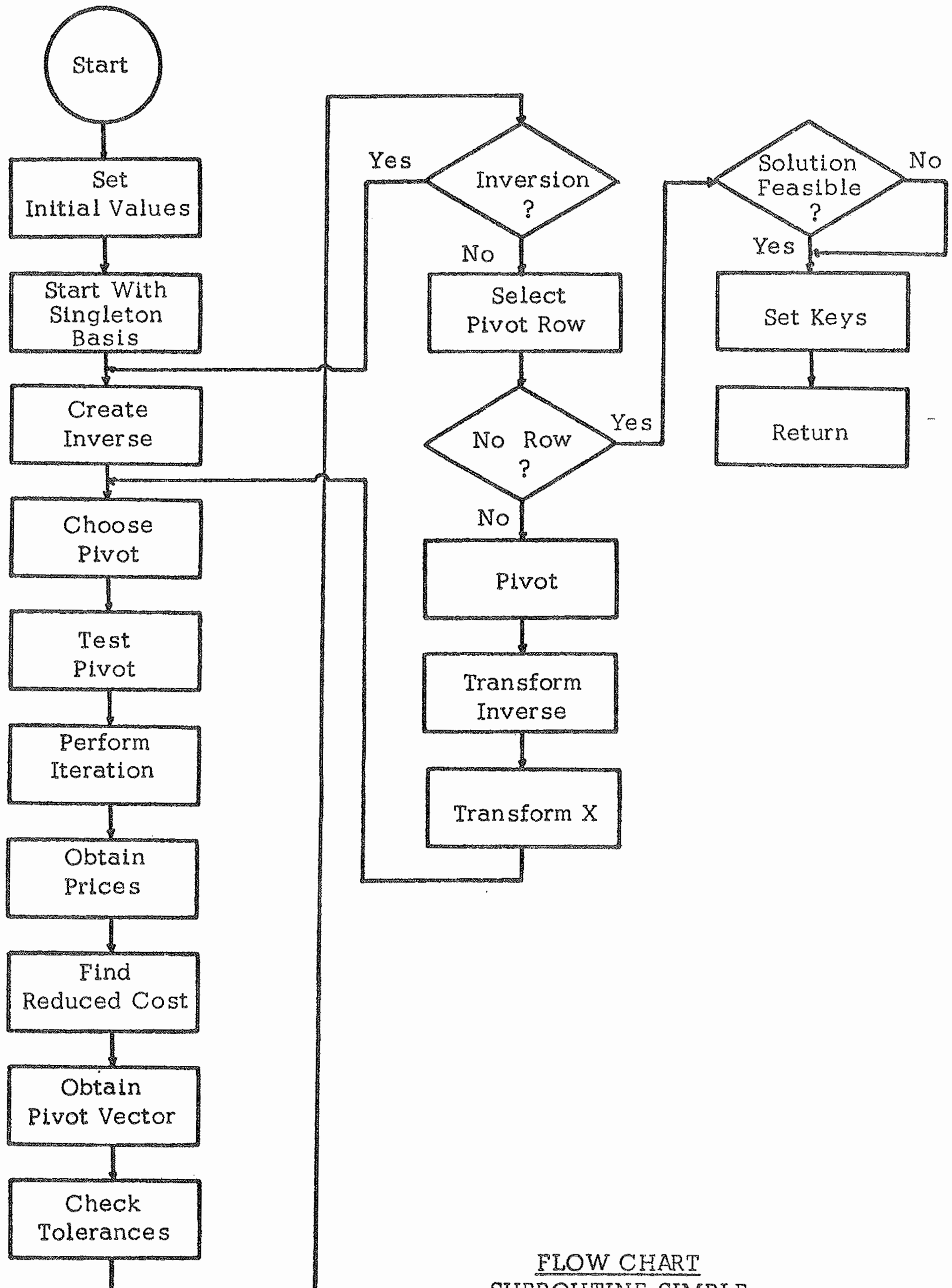
FLOW CHARTS



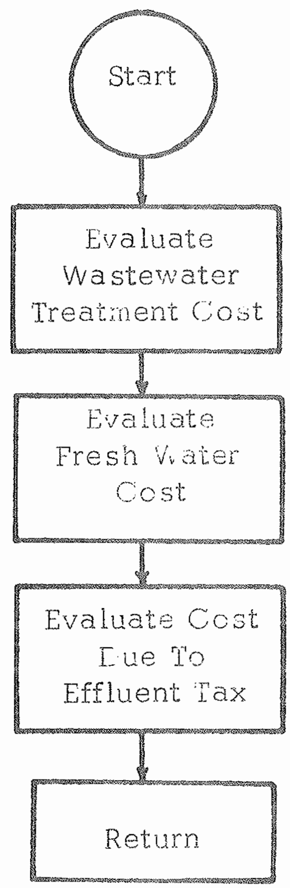
FLOW CHART
PROGRAM MONEI



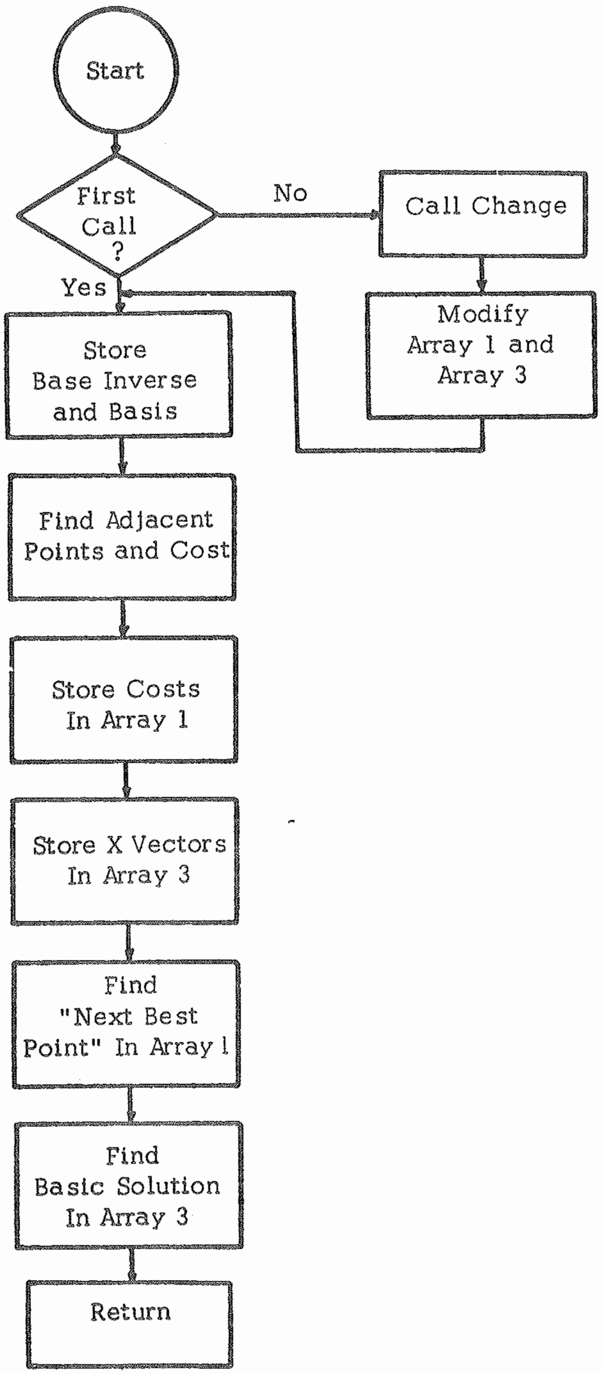
FLOW CHART
SUBROUTINE SEQUE



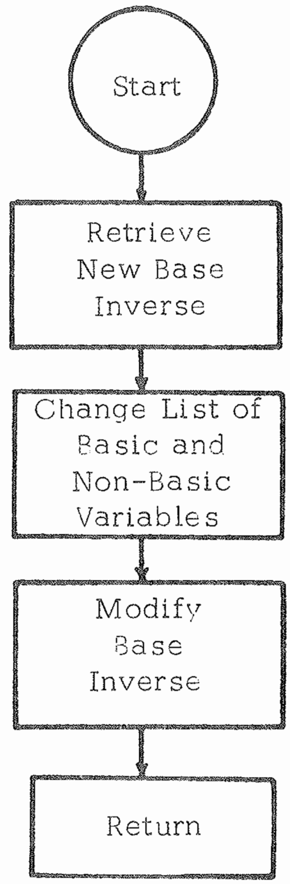
FLOW CHART
SUBROUTINE SIMPLE



FLOW CHART
SUBROUTINE COST 2



FLOW CHART
SUBROUTINE MURTY



FLOW CHART
SUBROUTINE CHANGE

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