Technical Report

A NETWORK MODEL FOR URBAN WATER SUPPLY SYSTEM INCLUDING DESALINATION AND WASTEWATER RENOVATION

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March 1974

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To

Chairman (Research)
IIMA

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Title of the report A NETWORK MODEL FOR URBAN ....RENOVATION.....

Name of the Author ..Shishir K. Mukherjee..

Under which area do you like to be classified? [illegible]M..................

ABSTRACT (within 250 words)

Most urban areas are facing an ever increasing demand for fresh water due to population and industrial growth. The paper presents a network programming model to evaluate alternatives for supplying water from various sources - treated fresh water, desalinated sea water and renovated waste water - to satisfy future demands for multiple water use in coastal cities at minimum cost. Water demand projections for municipal, industrial, agricultural and recreational use are specified in terms of their geographical locations, quantity and quality specifications for a future data. Costs of water to match these demands from different sources any by desalination and renovation areassumed known. The network programming computer model can accommodate non-linear costs of water development, treatment and conveyance and uses an iterative technique to obtain a minimum cost solution. The network model described is quite general in the sense that it can be applied to other areas such as waste disposal and water pollution control, solid waste management, air pollution control, pipeline optimization and transportation studies.

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A NETWORK MODEL FOR URBAN WATER SUPPLY SYSTEM INCLUDING DESALINATION AND WASTEWATER RENOVATION*

Dr. Shishir K. Mukherjee

Most urban areas are facing an ever increasing demand for fresh water due to population and industrial growth. The paper presents a network programming model to evaluate alternatives for supplying water from various sources - treated fresh water, desalinated sea water and renovated waste water - to satisfy future demands for multiple water use in coastal cities at minimum cost. Water demand projections for municipal, industrial, agricultural and recreational use are specified in terms of their geographical locations, quantity and quality specifications for a future date. Costs of water to match these demands from different sources and by desalination and renovation are assumed known. The network programming computer model can accommodate non-linear costs of water development, treatment and conveyance and uses an iterative technique to obtain a minimum cost solution. The network model described is quite general in the sense that it can be applied to other areas such as waste disposal and water pollution control, solid waste management, air pollution control, pipeline optimization and transportation studies.

INTRODUCTION

Most urban areas are facing ever increasing demands for fresh water due to population and industrial growth, and per capita increase in water consumption. Often costly water development and transportation projects must be undertaken to meet these demands. The problem is further complicated by public demands that receiving waters for wastes should be maintained at acceptable quality levels which consequently requires the use of costly waste treatment

* Presented at the meeting of Urbanisation Group of National Committee on Science Technology, Yojana Bhavan, February 19, 1972.

methods to accomplish this. Many municipalities will soon have to provide at least secondary treatment to their waste waters prior to ultimate disposition.

Since available sources of fresh water are limited, it is becoming increasingly important for some urban areas to consider renovation of these treated waste waters and the use of desalinated sea water as additional sources of water. Desalinated sea water has been generally a prohibitively expensive supply alternative for many uses. It is a source of supply which is of growing importance in water short coastal areas, particularly for industrial users. The tourism industry, which can usually pay a relatively high price for water, and industries using ultrapure water are potential users of desalted sea water.

Public health considerations have usually resulted in strong objections to the direct reuse of renovated wastewater for human consumption. There is also a traditional and psychological resistance to re-cycling renovated wastewater. Nevertheless, there is growing awareness that renovated wastewater can be used for irrigation and certain industrial purposes. Considerable research is being directed toward resolving public health problems through economically attractive treatment steps. Where higher levels of treatment are now required before discharging wastewater in receiving waters, reclaimed water suitable for municipal, industrial or agricultural use could be obtained at a low marginal cost. Water renovation and reuse, subject to public health and aesthetic —

acceptance, can solve the problem of water supply and water pollution control simultaneously and may prove economical for many urban communities.

The complexity of economically evaluating the large number of feasible alternatives in the design of such a water supply system consisting of numerous sources, and demands of various types, treatment plants, storage and conveyance facilities, waste treatment and disposal processes, is obvious. The use of a "Systems approach," in which operations research analysts closely participate with the engineers, planners, and municipal authorities in the design and implementation of such schemes is definitely needed. The paper presents such an approach in the development of a network model for designing a minimum-cost water supply system.

WATER SUPPLY/WASTE DISPOSAL SYSTEM DESCRIPTION

The basic elements of a Water Supply/Waste Disposal System including the use of desalinated sea water and renovated wastewater are illustrated in Figure 1. Water demand projections for municipal, industrial, recreational and agricultural uses are made available in terms of their geographical locations, quantity and quality specifications for a future year for which the system is being planned. Water sources are specified as to the maximum quantity available, quality and unit cost. Water treatment processes are defined to match the quality of treated water to the demand quality requirements. Alternative ways of meeting the demands from various sources

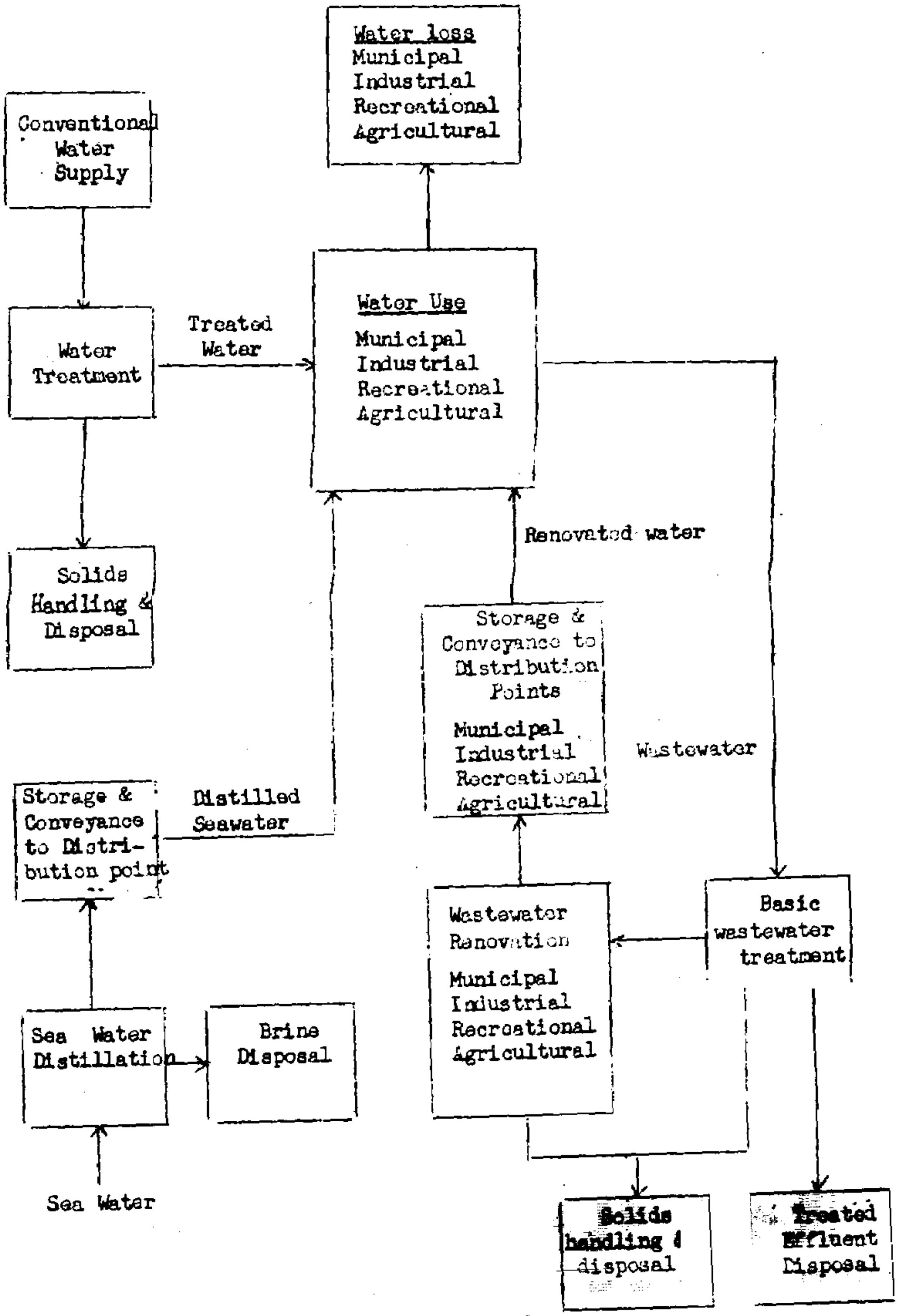

Figure 1: Basic Elements in Water Supply and Wastewater Disposal Systems

of treated water are proposed and the ones considered infeasible from engineering and economic judgment are deleted from further consideration.

Allowing for various losses in use, the municipal wastewater is considered as another source of water which could be recycled into the system after adequate treatment and purification subject to acceptance by public health standards and aesthetic considerations. If renovated wastewater is considered unacceptable for municipal use (due to possible danger to public health and traditional and psychological resistance by people) or process use in industry (due to build-up of soluble salts in renovated water), it could at least be used for various agricultural and industrial cooling purposes. Various combinations of processes are considered for the treatment and renovation of wastewater including primary, secondary, activated sludge and trickling filter treatment; chlorination; lime treatment and ammonia stripping; dual-media filtration and electro-dialysis. The combined processes are designed to produce water quality to match demand quality requirements. The possible locations of the treatment plants are decided from engineering-economic judgment and geographical considerations.

For some urban areas, desalination of sea or brackish water may become another source of water. Convenient locations for such plants are considered. Often blending of desalted sea water with fresh water from other sources with high dissolved solids content will produce acceptable water at a moderate cost. Finally some storage facilities must be included at various points in the system to accommodate seasonal and diurnal fluctuations.

The water supply/waste disposal system consisting of the available multiple source of water and demands, alternative ways of supplying these demands from the given sources, alternative processes for treating fresh and wastewater and adequate storage and conveyance facilities as its elements is represented by a conceptual network in the model.

COST DESCRIPTION

Since it is desired to design a least-cost system to satisfy all the demands (if feasible), the total system cost is the measure of effectiveness. Unit costs as a function of flow in million gallons per day (mgd) are developed for each activity-drawing water from sources, treatment, storage and conveyance facilities needed to supply given demands, wastewater collection, treatment and disposal, desalination, etc. and expressed as cost per thousand gallons of water. The capital costs are amortized with suitable interest rate and added to the operating costs. The total system cost could be determined from the unit costs for any pattern of flow which satisfies a given demand.

Cost functions are developed for each activity in the water supply/waste disposal system represented by arcs in the network description of the system. The costs as a function of flow rate are nonlinear in general, basically due to the economy of scale [illegible]lved in most of the processes. A typical cost function for water treatment is presented in Figure 2, where total cost per thousand gallons is plotted against treatment plant capacity in mgd.

It is observed that unit costs (per thousand gallons) when plotted against flow on a log-log paper result in linear or piece-wise linear curves. The basic equation representing the unit cost functions is thus derived by determining values at two points on the same linear segment of the graph and is represented by:

$$C = aq^{-b}$$

where

$$b = \frac{\log(c_1/c_2}{(q_2/q_1)}$$

$$a = \frac{c_1}{q_1^{-b}}$$

C = unit cost (paise/1000 gal.)

q = flow rate (mgd)

c_1 = unit cost(paise/1000 gal.) corresponding to point 1 on the curve

c_2 = unit cost (paise/1000 gal.) corresponding to point 2 on the curve

q_1 = flow rate (mgd) corresponding to point 1 on the curve

q_2 = flow rate (mgd) corresponding to point 2 on the curve

In case where the cost function can not be plotted on a log-log graph as a single straight line, the curve is closely approximated by two or more straight linesand break-points in the piece-wise linear curve is used for computing a set of values for the constants

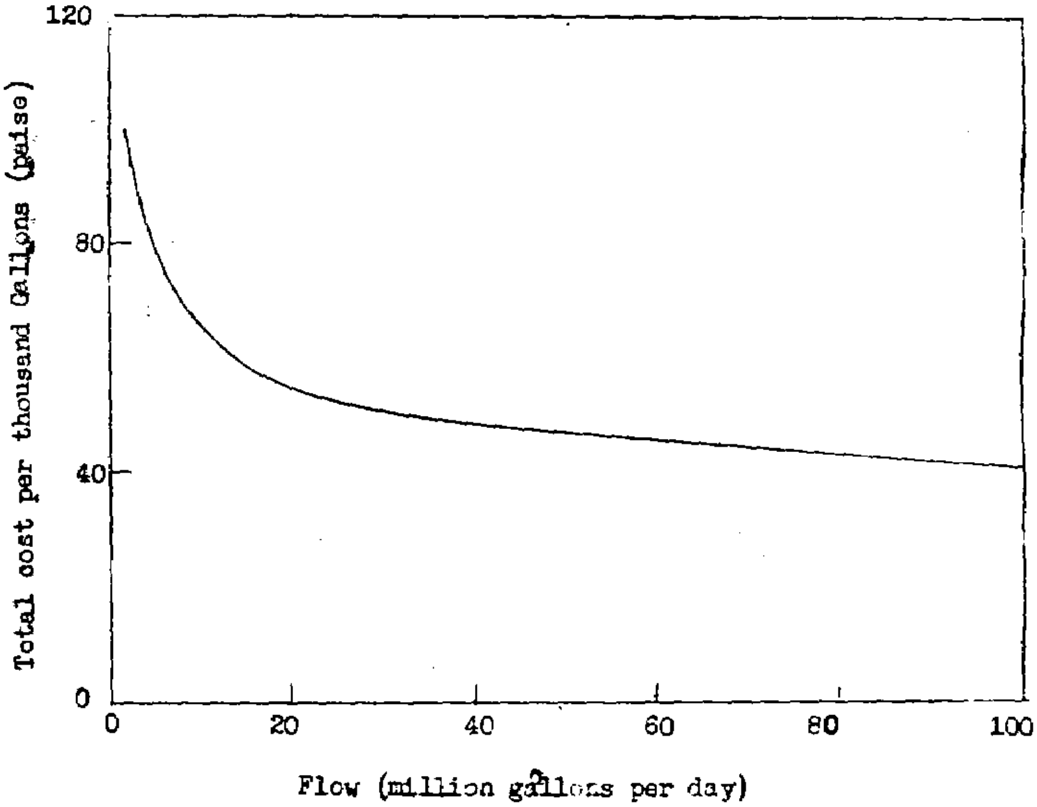

Figure 2: Typical Water Treatment Cost Data

a and b for each linear section of the curve.

The non-linear cost functions considered in the model, which are more realistic than linear descriptions of cost usually assumed in similar studies, cannot be accommodated directly in available network flow algorithms which assume linear costs of flow. They are handled by an iterative computational technique described in the following section.

NETWORK PROGRAMMING MODEL DESCRIPTION

The problem of determining the least-cost design of the Water Supply/Waste Disposal System is formulated as a problem of finding the minimum-cost flow pattern in a conceptual network. The conceptual network model is developed by incorporating the various activities, their limiting capacities and unit costs on the physical layout of sources, treatment plants and demands connected by conveyance lines. Network flow theory (1), a very useful tool of operations research applied in the optimization of systems described by physical or conceptual networks, is applied as a solution technique.

Minimal Cost Flow Problem in a Network

A network consists of a collection of elements called nodes or vertices some of which are connected by branches or arcs. The nodes may be divided into three categories - "sources" at which flow is generated, "sinks" at which flow is consumed and "intermediate" nodes at which flow is conserved. The arcs are usually associated with minimum and maximum capacities of flow (in one or both directions) of some commodity (fluid, electricity, consumer goods, money) per unit time.

One of the common problems connected with flows in network is to determine the maximum flow through network with specified arc capacities. It is plausible to assume a cost for flow in each arc of the network. The costs may be linear or nonlinear functions of the flow. An interesting problem with application to the water supply/waste disposal system is to find the distribution of flow that minimizes the total cost of transporting a given flow value through the network, if feasible. In constructing the conceptual network to represent the water supply/wastewater disposal system, an 'arc' is assigned (Figure 3) for each function or activity in the system, e.g. drawing water from a fresh water source, treatment processes, conveyance routes, desalination, etc. Thus for wastewater the arcs WP, PS and ST represent various levels of treatment which make the water suitable for irrigational, industrial and municipal use. An arc has two 'nodes' as its terminals and an arrowhead specifying the direction of flow. All sources become 'source' nodes and all demands become 'sink' nodes in the network. Maximum available flow at sources, specified demands and capacity limitations of processes are handled by assigning each arc a minimum and a maximum capacity for flow. If any arc must carry a specified amount of flow.

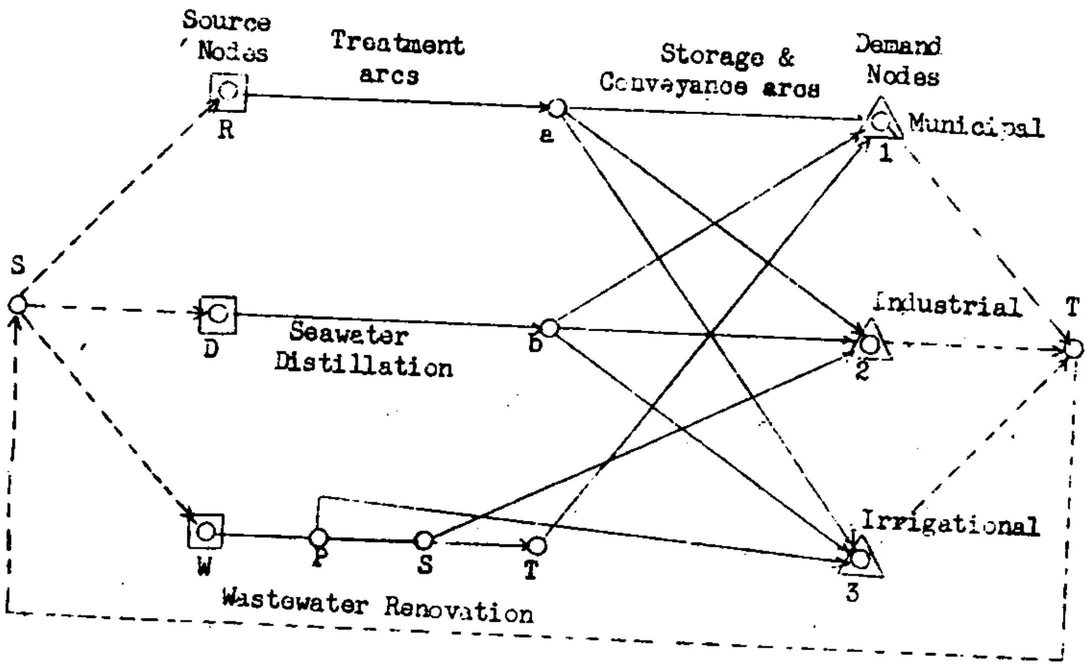

Figure 3: Sample Network to Illustrate Arcs and Nodes

The mathematical formulation of the minimum cost network flow problem for a network is described in (1).

There are a large number of feasible flow patterns in the network to satisfy the specified demands from the available sources. The most powerful computational method for solving minimum cost network flow problems with constant unit costs (representing linear cost functions) is the Ford-Fulkerson "out-of-kilter" algorithm (1) which minimizes total cost on the network while circulating feasible flow through it.

The out-of-kilter network algorithm starting with an arbitrary set of flow values, either feasible or infeasible, and unit arc costs, builds flow patterns in the network with the goal of fulfilling the flow demands at minimum total cost. The program simultaneously checks the feasibility and optimality criteria of a flow solution. It checks the feasibility criteria by ascertaining that all flow demands are met and no capacity constraints are violated. The optimality criteria for an arc is determined by the relative values of specially defined node prices at the extremities of the arc, the arc cost and the flow value in relation to lower and upper bounds on the arc.

Any arc for which the feasibility and/or optimality criteria is violated is said to be out-of-kilter. The flows in these arcs are changed by using a flow circulation technique and if that is not possible the node prices are changed which may allow flow changes. The algorithm brings out-of-kilter arcs into kilter while maintaining in-kilter arcs in kilter. Eventually, all arcs are put in kilter, or it is learned that certain arcs cannot be in kilter simultaneously which indicates that the problem is infeasible. If integer values are used for all the variables, costs and flow bounds, it is easily proven that the algorithm terminates in a finite number of steps (1).

A Network Analysis Computer Model which uses the "out-of-kilter" algorithm described above as a subroutine has been developed to determine the minimum cost flow pattern in the urban water supply network with nonlinear costs. As the basic algorithm can only accommodate linear arc cost functions, special techniques are necessary to handle the nonlinear functions described in the last section.

The generalized flow diagram of the Network Programming Model developed for this application is illustrated in Figure 4. It basically consists of three following programs controlled through an executive routine.

<u>Preprocessing Programme</u>: Because of nonlinearity of most unit cost data, as illustrated for water treatment in Figure 2, the optimum flows determined by the first pass through the network programme will, in general, not be the least-cost solution. To account for the nonlinear cost functions and to formulate the input data in the correct format an iteration procedure was developed which uses a preprocessing programme and a recosting programme, in conjunction with the network programme.

The preprocessing programme computes the unit cost as a function of flow rate for each activity in a network from basic

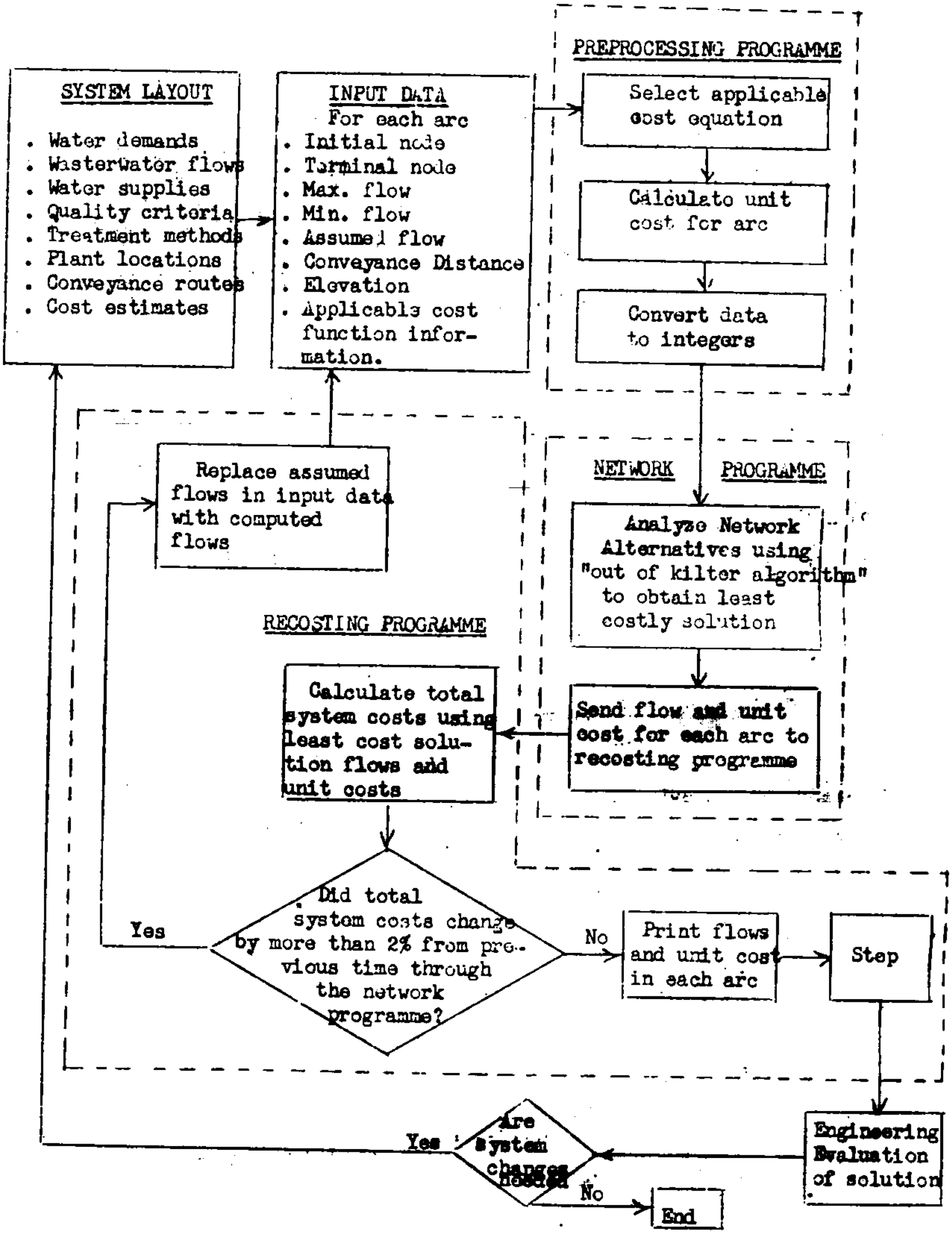

Figure 4: Model Components

information regarding the process costs and physical parameters such as distance, elevation, type of land etc. Thus it consists of a series of equations which are used to convert the system cost information into unit arc costs expressed in nearest integers (in small monetary units) to be subsequently used in the optimization procedure of the network programme. The flow rates used in the calculations are initially assumed values in the input data for the network. These initial flow values are replaced by corrected values generated by the network programme, resulting in new unit costs. As the routine is repeated, the computed flow rates at successive iterations converge and an optimum flow system is determined.

Network Programme: This programme, as described earlier, essentially uses an "out-of-kilter" algorithm to analyze alternative flow patterns for the given unit cost data and arrives at a least-cost flow pattern. Thus it solves the problem for a linearized network.

Recosting Programme: The recosting programme is used to correct the error introduced by linearizing the problems. It takes the least-cost solution from the network programme and reassigns flows in the input data for the preprocessing programme. The whole computational process is then repeated with the preprocessing programme computing new unit arc costs for the newly assigned flows and the network programme finding a new least-cost flow solution. The total system cost is computed after each pass through the three programmes and compared to that at the last pass. If the percent change in total costs is greater than a fixed eoor value (1 to 2%), then the iterative technique is continued. Otherwise the computation is terminated and the final solution printed as the optimal solution. Accuracy of the model is increased by decreasing the fixed error value, though it may increase the number of iterations if the problem does not converge quickly to a solution. In all the cases where the programme was used, convergence to a solution was obtained within a few (4-5) iterations of the recosting programme.

The nonlinear cost functions included in the Network Programming Model are non-convex and thus are not mathematically suitable for minimization purposes. In specific situations, there may be possibilities of obtaining locally optimum solutions. The recosting subroutine in the computer programme makes it converge to such a locally optimum solution, which may be globally optimum in most cases. However, specific measures and checks and bounds must be included in the programme to provide sufficient assurance that the solution converges to the real optimum. This is an inherent difficulty frequently encountered when cost functions represent economies of scale. To obtain sufficient assurance that a globally optimum solution has been obtained, the programme can be solved starting at several random beginning solution. If the same optimum solution is obtained in all cases then one can state with some confidence that the real least-cost solution has been obtained. Using a slightly different computational scheme, it is also possible to obtain a lower bound to the globally optimum solution cost at each iteration and thus ascertain that a solution sufficiently close to the globally optimum has been obtained.

EXAMPLE NETWORK PROBLEM

In order to illustrate the general type of analyses that can be performed by the network model, the following example problem is presented.

The primary elements of the problem selected are illustrated in Figure 5. For this problem there are two municipal water demands (M1 and M2), one industrial cooling water demand (I1), one industrial process water demand (I2) and one agricultural irrigation demand (A1).

The water supplies considered for this example consist of two conventional water treatment plants (S1 and S2), one seawater distillation plant (D1), and two wastewater renovation plants (R1 and R2), all shown in Figure 5. The water demands and water availabilities assumed for each supply are also shown in Figure 5. As can be seen, each type of demand can be supplied from two or more alternative supplies. The fundamental problem to be solved is therefore to select the least-cost alternatives to supply the indicated demands.

For each activity (i.e. treatment, storage, or conveyance) required in the system, the unit cost was determined as a function of flow rate (mgd) and included in the preprocessing programme discussed earlier.

A solution for the example network problem was generated using the network model (Figure 6). In this solution, the municipal demand M1 was supplied by the conventional water source S1

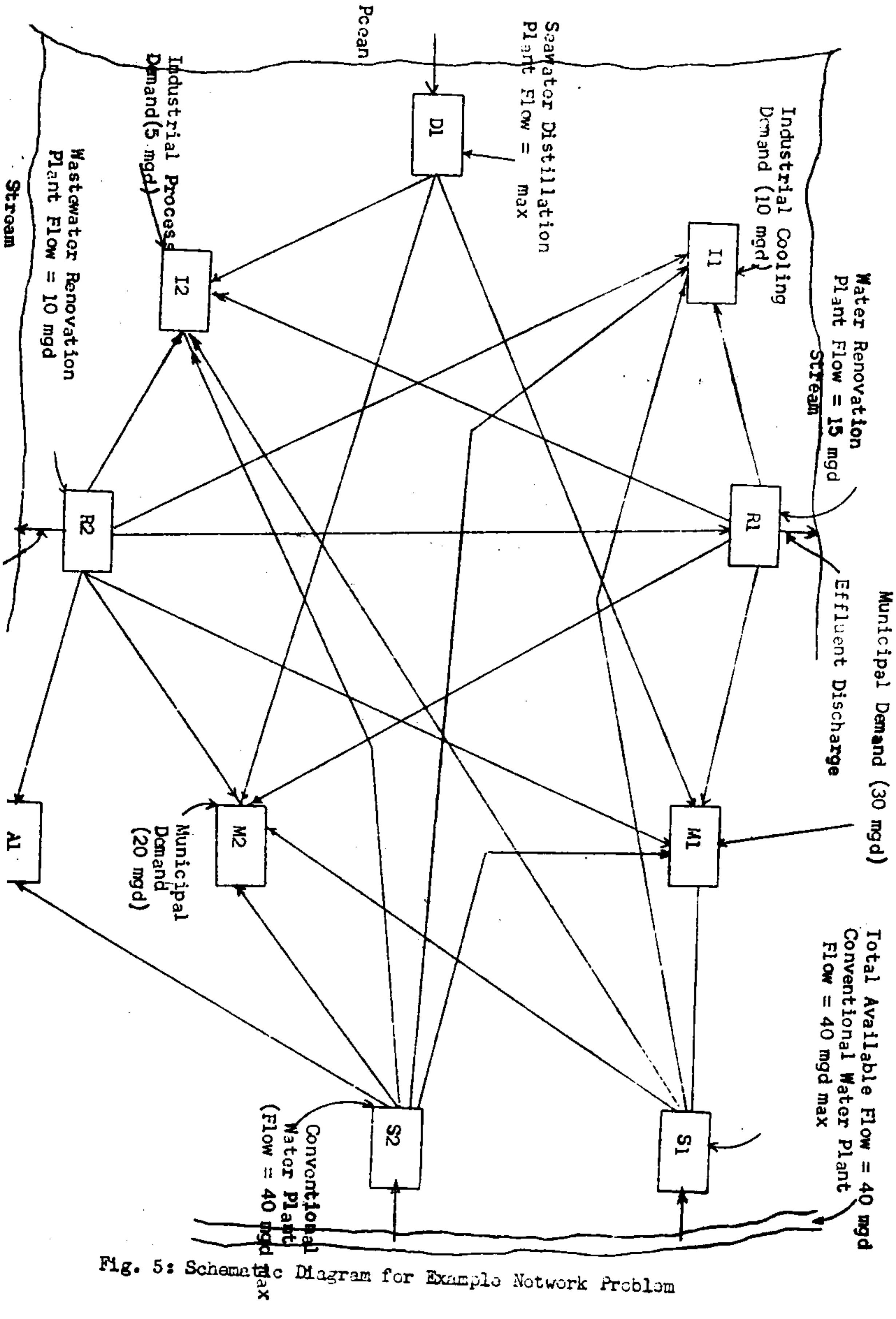

Fig. 5: Schematic Diagram for Example Network Problem

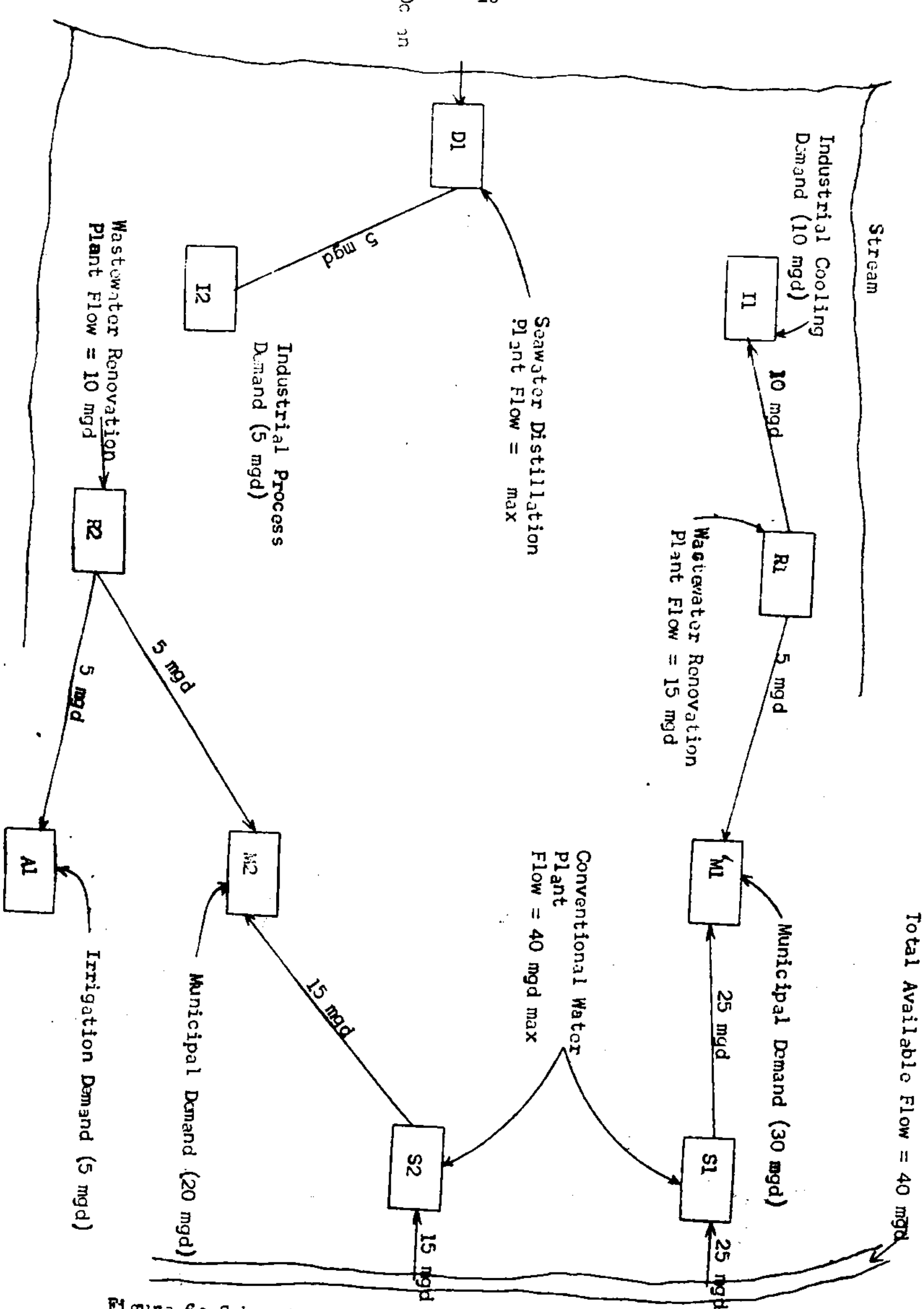

Figure 6: Schematic Solution of Example Network Problem

and the renovated wastewater source R1. Municipal demand M2 was supplied by the conventional water source S2 and the renovated wastewater source R2. The industrial cooling water demand I1 was supplied by renovated wastewater from source R1 and the industrial process water demand I2 was supplied by the distilled seawater source D1. Agricultural irrigation demand A1 was also supplied by renovated wastewater from source R2.

The results of this solution indicated that, in this case, the construction of two water treatment plants and two wastewater renovation plants was preferred to one large plant of each type. Thus, the economics of scale associated with larger facilities were offset, in this example, by the reduction in conveyance requirements. As pointed out earlier, the indicated use of renovated wastewater for the municipal demands requires further research and approval by public health officials. However, based on the assumptions and cost data used in the example problem, the potential feasibility of using renovated wastewater for municipal demands appeared as a possibility.

Although the example problem and the solution presented are relatively simple compared to a large municipal area, other preliminary investigations have been conducted using the network model on three large cities. The results from those investigations, as well as the example problem presented, indeed indicate that the model can be used as a powerful tool in planning complex water supply-wastewater disposal systems.

DISCUSSION AND CONCLUSIONS

The Network Programming Model was used to conduct preliminary studies of the water supply/waste disposal system of three large cities in USA. For each of the cities the geographical area was divided into a number of water demand centres, classified into municipal, industrial (process and cooling), irrigational (crop and non-crop) and recreational water demands. From available estimates of population, industrial and agricultural land use growth, water demands for a future date is specified.

Various available and potential water sources were identified and for each source information on available capacity, quality of water and unit costs were collected. The costsused were collected from various published sources. The results of these studies indicated that in certain cases there is economic justification in re-use of reclaimed wastewater. Desalinated seawater is usually brought into the solution to supply high quality water required for industrial process use or for obtaining acceptable water by blending it with water containinghigh amounts of total dissolved solids. A linear programming model where water from different sources are blended for supplying water for municipal, industrial, agricultural and recreational use for each of which multi-component quality standards are specified, will be the subject of a future publication.

Parametric studies can be done using this model to evalaute the effect on the total system cost of changes in input flow, capacity and cost information, innovations in the field of desalination, water and waste treatment and changes in public policy regarding the use of renovated wastewater and water quality requirements in the receiving waters, where treated wastewater (if not cycled in the system) is discharged. The Network Model and the concept of minimizing cost of flow through a system network is quite general in the sense that it can be applied to other areas of urban planning. The author has used the Network Model in tandem with predictive estuarine water quality models (3) for complete water resources planning including water supply, waste treatment, waste disposal and water pollution control in the receiving waters. Similarly, it can be used for air pollution control at minimum cost in conjunction with regional air pollution models. It can also represent solid waste collection, processing, storage and disposal system. The Network Model has also found wide application in studying urban transportation system.

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