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MOHAMED ABDO AL-AWADY

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CHAPTER I

INTRODUCTION

A serious problem of water resources in arid or semi-arid areas (throughout this dissertation arid areas will be used synonymously with desert lands) has been created because of the rapid growth in population, improvement in the standard of living, and an increase in commodity production and service industries. The almost unlimited economic possibilities in the arid areas have made it most urgent that a way be found to produce more usable water. Since World War II there has been a rapid development of desert areas (United Nations, 1965). They contain and produce the world's major oil production and other minerals.

In recent years most water resources study has concentrated on one or more of the following: flood control, irrigation, recreational use of water, hydroelectric, navigation, domestic and industrial water supply, watershed management, fish and wild life, pollution abatement, insect control, drainage, sediment control, salinity control, artificial precipitation, employment, public works, and new water resource policies (Ghow, 1964).

The discussion and the attempt to solve the problem of water resources have been confined almost entirely to what may be called the conventional areas. Little has been done in evaluating and solving the problem of water resources in desert areas, where there is no surface water and the rainfall is rare. Economic growth in these areas is vital, but such development depends entirely on the availability of economic water supply.

Water shortage is not always caused by a lack of water but might be a lack of water resources development. If economic growth and the standard of living are to develop, it is essential to make an immediate and comprehensive survey of present and future water demands.

Every method of getting usable water should be completely investigated so that the most feasible and economic water supply can be determined. Such combinations as brackish ground water with distilled water might be studied; a blended effluent and brackish water might be considered as an adequate source for use in industry or agriculture.

There are new processes by which sewage plants produce an effluent that is entirely safe and suitable for certain purposes. The disinfected effluent is of adequate quality for some types of irrigation and industrial use without any further treatment, or it can be given an additional treatment and then mixed with distilled or underground sweet water to make it suitable for use in nonpotable domestic needs.

Another aspect to be examined, when investigating water resources, is the distance from the suggested resource to consumer. This is a matter of economics, since it hinges on an assessment of total cost of water, including conveyance, from all possible sources. This cost might be an important factor in the total cost of water, and a comparison of total costs must be made for water delivered to the consumer.

The ideal situation would be to find a number of water resources. Exploration of various combinations of water from all possible sources and means of conveyance should provide the best solution to the problem of water supply.

Research Plan

The primary objective of this dissertation is to construct and test a mathematical model for water resources and conveyance for arid regions in which there are:

1. Different sources and alternate ways for conveyance to users,

2. Limited resources,

3. Projected needs for more facilities to meet increasing future demands.

The usable resources of water will be affected by the means and cost of getting the water to wherever it is needed. A solution must be found to use all resources to achieve maximum returns. Another and equally important factor is to determine the best combination of resources, the most economical means of conveyance and the quantity of water required. This would make it possible to maximize the effectiveness and assure utmost economy.

One of the tools recently associated with optimization techniques is linear programming. With the development of the simplex technique (Ficken, 1961) for solving linear programs, it is possible to find feasible solutions from which the optimum solution can be determined.

The secondary objective is to demonstrate the optimization of a water resources model using the State of Kuwait as an example. The present water resources in Kuwait are:

(1) distilled water; (2) underground brackish water, and (3) underground sweet water (throughout this dissertation sweet water will be used synonomously with underground fresh water) (Witty, 1965). The only means of water conveyance at present is by tank trucks (International Bank, 1965). The least cost combination of these resources can be obtained for domestic and non-domestic purposes as a function of several variables, e.g., source of water, population, quantity of water required, and means of conveyance.

It is essential that all these variables and their interactions be well defined and their effect on water resources and uses be specified. The variables which will be considered are:

(a) Population, its future needs and density within the water resources region,

(b) The sources of water for domestic and non-domestic uses,

(c) Quantity of waters for domestic and non-domestic uses,

(d) Means of conveyance of water from different sources to consumers.

The responsibility of maintaining an adequate water supply for the State of Kuwait has become a major problem in recent years (Quality Publications, 1965). There are gross deficiencies in the present system, although the government has successfully supplied the people with sufficient water. Even though the largest desalinization plant in the world, located in Kuwait, is now producing thirteen million gallons a day, this will not be enough to support population growth, industrial expansion or expected agricultural plans. A source anticipated but not yet incorporated is the reuse of effluent water. With four sources of water there is a justifiable hope that the State of Kuwait can meet water needs in the future. The unit cost for use of these sources plays an important factor in limiting its production and conveyance to satisfy the requirements of an expanded demand at a minimum cost. Solutions which might be considered are:

(1) The use of distilled water for domestic purposes,

(2) The use of underground brackish water for industry and domestic purposes other than drinking,

(3) The retention of sweet water as a reserve and a factor of safety,

(4) The use of water from sewage plants for agricultural purposes,

(5) The use of dual distribution systems for drinking and non-drinking water,

(6) The decision criteria for installation and changing to a new system,

(7) The arbitrary limiting of use or short term and long term plans,

(8) The determination of the use or non-use of certain resources in given time periods.

The study of water resources for the State of Kuwait should provide guidelines for extrapolating from present knowledge of unit cost to a new and improved use of their water resources in an optimal way. This can be done by relating the costs of different sources, means of conveyance, determination of specified quality and quantity required.

CHAPTER II

ENGINEERING AND ECONOMIC ANALYSIS

Introduction

There are two phases in any efficient study of a water resource development problem.

First, the most advanced available technological facilities and knowledge must be assembled and utilized. Second, complete economic analyses must be used to predict as accurately as possible eventual water processing costs and realistic consumer prices. Successful completion of these two phases of the problem will result in maximum efficient use of available water resources with minimum cost, and provide a base from which to project satisfactory solutions for future water needs.

If water is needed to sustain human life, economic considerations, i.e., minimum costs, should be subordinate to technological efficiency. If water resource developments are needed primarily for successful completion of irrigation projects and for industrial expansion, economic variables and technological requirements must be more carefully balanced.

In many arid areas, existing potable water can be conserved by decreasing waste; priorities should be established based upon water use relating to life sustaining functions. Both distilled and underground fresh water can be conserved through use of a dual distribution system which conveys both potable water for domestic use and brackish water for non-domestic use.

Despite topsoil dryness, little or no rainfall, and other conditions associated with desert climates, underground water usually is available either from local underground rock formations where meteoric water has collected, or from underground "rivers" flowing through permeable rock strata and having their origins in more temperate areas (United Nations, 1965).

Supplies of underground fresh water may be sufficient in many cases to supply arid areas with reliable quantities of economical water for domestic, industrial and agricultural uses. But in areas of extreme dryness, where no useful surface or underground potable water supplies exist, desalinization of sea of other available saline water offers the only practical water resource development method. Desalinization has now reached a stage of development and momentum at which it is visualized that wherever water needs are critical, where high-cost water is economically acceptable, and where there are saline water sources standby, desalinization can provide a solution to the shortage of water.

Following establishment of a primary fresh water supply, water re-use provides an additional possibility for developing water resources. A properly designed sewage treatment plant can produce an effluent of acceptable chemical and biological quality for both irrigation and some industrial operations. However, effluent water may contain detergents or other poisonous materials, rendering its processing impractical for drinking or other domestic purposes.

Recent studies indicate that water use in residency areas average about 200 gpd. Certain of these categories require clean pure water, such as lavatory, cooking and dishes, house cleaning, tub or shower and laundry. The requirements are not so high for toilet use, and it may be possible to recycle water for use in the toilet after it has been used initially for some of these other categories.

Tub or shower water augmented with lavatory and laundry water would be sufficient to meet the average toilet needs. This offers the possibility of reducing the water consumption by 39 per cent under the above use distribution (McLaughlin, 1968).

Following a survey and evaluation, water resource development of the desert areas may be restricted to one or a limited combination of sources. Ultimately, the reliability of a potential water source will be a major influence in its serious consideration. For example, desalinization, although probably the most expensive water supply in the area, could be the only acceptably reliable source.

Generally, in arid regions, a combination of water sources appears to be the most economical water resource development solution. The same principles which determine economically feasible underground fresh water resource development usually will apply to the evaluation of the underground brackish water and its development. If mixed with desalinated water, brackish water can be of acceptable salinity, and will satisfy domestic consumers. Desalinated water might be used as a primary source, leaving underground fresh water, if available, to satisfy daily and seasonal use peaks and the brackish for non-domestic uses.

In summary, when more than one source of water is available for development in an arid area, exploration of various combinations of water from all available sources can be economically advantageous and can produce the most satisfactory solution to water resource development problems.

Defining the System

The first step is to define the problem, set the objective and investigate all possible solutions. A schedule must be defined for procedure and adhered to in order to secure earliest possible results.

A map of the area concerned is necessary, and it must show all available water for domestic, industrial and agricultural uses. The map must indicate water obtained from all sources. The future needs of the population and urbanization must be carefully shown to present the actual needs for the present and the future. When the planning is defined, a preliminary screening technique might be used to reduce the number of alternative combinations to the one that has the most advantages.

Water Supply

Water supply in desert lands is a problem that is different from all other such problems in other areas. There are only four possible water resources that might be available; distilled water, brackish water, fresh water, and effluent water. The relevant characteristics of supply are quantity, quality, and availability measured according to the location of the supply and the distance to the area where the water will be used. A complete study of the four components of water resources and their inter relationship should be made.

Desalinated Water. The conventional water resource should be considered first. All alternative ways of obtaining potable water should be investigated thoroughly from the standpoint of both economical and technical feasibility. If a source of distilled water is presented, it should be determined if it will be the sole source now and in the future. In making a decision about distilled water, the following items should be carefully analyzed:

1. There are different processes by which distilled water can be secured; each one has its own advantages. The decision should be based on the most feasible solution for the area concerned from the following:

   a. Flash distillation,

   b. Multiple-effect boiling,

   c. Freezing,

d. Electrodialysis,

e. Vapor compression,

f. Ion exchange,

g. Reverse osmosis.

2. Examination of the dual purposes which supply desalinated water and at the same time produce enough energy to generate electric power, or the possible necessity of the use of desalinization plant for water only.

3. Study of location of the plant and consideration of whether desalinated water will be used with or without any other source of supply.

4. The capacity of the plant and its relation to the storage should be accurately established.

5. The salinity of the available water and whether it is sea water or brackish water must be determined.

6. A means of conveyance to the consumer is required.

Underground Brackish Water. Brackish ground water is an important source of water in areas of extreme dryness; however, the following factors need to be examined:

1. The natural field storage and its capacity,

2. The transmissibility of the aquifer and its geological formations,

3. The hydrological investigations concerned with:

a. Total storage,

b. Movement of water under the ground,

c. Capacity of the storage to recharge,

d. Rate of discharge.

4. The salinity of the water, whether it is distilled and/or a blend of sources of water,

5. The quality of the brackish water and ways of using such untreated water directly,

6. The location of the brackish water,

7. The means of conveyance to the consumer,

8. The pressure existing on the brackish water and whether the water is artesian or needs pumping.

Underground Fresh Water. Ground water originates through downward seepage of moisture falling on the land as rain, snow or ice. The water filters into the earth to a level below which all openings in the geological formation are saturated with water. To use this water again, it is essential and mandatory to study the same consideration, which has been mentioned for the underground brackish water, in addition to the following:

1. The location of the field with respect to the demand's area,

2. The treatment processes, if any, needed,

3. The determination of whether to use sweet underground water separately and/or to mix it with other water sources.

Water from a Sewage Plant. Water has the ability to dissolve some compounds and to carry others. The technology has been developed for processing sewage effluent to obtain any desired degree of purity. Although domestic consumption of this water is lagging, it has had a widespread use in agriculture. In an arid region effluent water might be a source for industrial and agricultural use, but first the following should be considered:

1. The quantity and the quality of the sewage water,

2. A correct analysis of all the components of the polluted water,

3. The technical approach for cleaning the water most economically,

4. The location of the sewage plant with respect to both the sewage processes and the water supply,

5. The means of conveyance and needs for additional distribution systems,

6. The determination of whether the effluent can be used following proper treatment or whether it will integrate with other sources to be more acceptable and

healthful for a specific use,

7. The obtaining of public acceptance for using sewage water where necessary.

Water Demands

Water demands are defined as the quantity of fresh water which is required for use by the three user categories, i. e. domestic, industrial, and agricultural, at a particular time. Analysis of water demand is a necessary premise to decisions concerning the present and future availability of water resources in the arid areas. All pertinent and available statistical data must be collected and analyzed, in order to assess present and future demands.

The urbanization, present or potential, which draws upon the water resources of the system, and the requirements of water used (quantity and quality) for domestic, industrial, and irrigation development can be presented as follows.

Domestic Uses. The urbanization of the area must be identified. All present and future planning should be shown in the following details:

1. The residential area with complete record of population,

2. The area of each zone and sub-zone,

3. New zones and/or the expansion of the existing ones,

4. Population density,

5. Estimated population growth,

6. Water consumption on a per capita basis,

7. Future water consumption on the same basis,

8. The quantity and quality of water for present and future needs.

Industrial Uses. The industrial area must be thoroughly studied for the following information:

1. The quantity and quality of water for industry,

2. The area of each industrial zone and sub-zone,

3. An estimate of the expected expansion of new industry and their probable water needs,

4. The peak demand for water, and consideration of the need for water to fight industrial or home fires.

Agricultural Uses. Agricultural areas should be investigated for the following:

1. The area of ranches and farms,

2. The size and types of crops in each area,

3. The quantity of water needed for these crops,

4. The means of conveyance.

Development

When accurate knowledge of all needs has been obtained, there is yet another step to be studied. It is the development of the existing resources and a plan to establish a new relationship between all sources and the quantity and quality of the needed water. This is necessary because the needs for the present and the future are vital to the people and the land. Development could require the enlargement of the capacity of the existing water supply facilities and/or the development of new facilities and capacities. All variables concerning any source of water must be studied, and the most suitable and economical method determined. Reid (1967) has identified four planning steps, in the development of water resource systems; he stated,

> "The first step is identifying the objectives.
>
> What kind of goals or objectives are possible? Economic efficiency is a wonderful goal, but efficient from whose standpoint? National efficiency, regional efficiency? Income redistribution is another goal. We may have social objectives or aesthetic ones. Recently the President spoke of making the Potomac River beautiful. That is an objective."
>
> "The second step is translating the objectives into the specific goals which the plan must meet.

The third step is the formulation of a plan. We planned, designed and analyzed cost and benefits. We maximized our benefits or minimized our cost.

The last step in basin planning is analyzing and evaluating the consequences of the plan.

. . . the determination of capabilities. This is an inventory of management measures.

. . . a preliminary look at a large variety and number of management possibilities; eliminate quickly those which serve no discernable need and then after preliminary engineering analysis of still a relatively large number, screen out those which are clearly unfit due to exorbitant cost or on the basis of imperative social considerations.

. . . we test the plan and refine the details to a point where we can make recommendations. . . first analyze the physical performance; secondly, we must analyze the economic performance; lastly, the plan must stand the test of the comparison of the result with the objectives." (Reid, 1967).

System Design Variables, Parameters and Constants

After all developments have been studied, and available data set up, the physical limits for the suggested improvements should be presented. There will be three types of design variables:

1. The physical facilities, which include the capacity of the distillation plant, the quality and quantity of the sewage water, irrigation, industrial and other water distribution systems,

2. System outputs which define the quantity needed for the area to satisfy all the requirements in the present and the future for agricultural, industrial, and domestic uses; the quality of the water for each category must also be determined,

3. System policy parameters which include the allocation of distillation plants, stand-by units, the policy of leaving one source for peak or emergency use, the blending of one source with another, the operation cost, depreciation and maintenance policy.

Physical Functions, Parameters, and Constants

Physical functions represent a physical relationship between the different elements of the system such as:

1. Distillation plants, and cost production,

2. The constant daily water consumption, the variants in daytime and in different seasons,

3. The capacity of the conveyance system and its unit cost,

4. The maximum capacity of each resource,

5. The relationship between the separate or the combined needs of each resource.

Operating Procedure

The relationship between the design variables, the physical functions, parameters, and constants will convey essential information about the water-resources system in the arid areas, whose characteristics are to be presented in a mathematical model. The purpose of the model is to trace the behavior of the system over the different variables, parameters, and components of the water resources. Initial conditions will be determined, inflow from different sources, and specific targets will be set. Structural and resource constraints will be identified.

There may be arbitrary policies for distillation, pumping water, and means of conveyance to meet the specified target, which should be associated with an optimal operating policy and design. It might be impractical, but with careful screening of the unpromising solutions, essential parameters, variables, constants, and limiting policies can be established, tested, and the best solution near the optimal one can be located.

Cost and Benefit Functions

Building a mathematical model for a water resources system involves selecting all available parameters and constants with great accuracy, allowing for future needs. In any design of a water resources system, the analysis must include the benefits and costs. Such analysis should present an estimate for the economic value to the area for increase or decrease in goods and services with and without this project.

The benefits and costs should be determined from the same point of view and on comparable standards for time and place of occurrence. The measurement standards used in analysis, such as interest rates, risk allowance, and period of analysis must be exactly the same.

The relationship between the water supply and demand can be presented in the form of a production function. The input will be all water resources, land, construction materials, and manpower. The output will be suitable water for municipal, industrial, and agricultural uses. The cost of all input must be calculated to represent the value of all goods and services used for the establishment, maintenance, and operation of the project. To obtain such cost it will be necessary to analyze the components of cost function.

Cost Function

A functional relationship between cost and production for distilled water, brackish groundwater, fresh groundwater and effluent water must be presented. The important two factors of costs (Samuelson, 1967) are:

1. Fixed cost: which is the carried cost regardless of the plant production, and is composed of capital cost, depreciation, interest, insurance, and maintenance activities.

2. Variable cost: which will depend on the quantity and quality of water produced.

A functional relationship between cost and production for the four mentioned resources should be presented as follows:

Distilled Water. Serious consideration should never be given to building a desalinization plant unless natural sources of fresh water are known to be either absent or totally inadequate to satisfy the demand. At Present, desalinization is quite expensive when compared with most traditional methods for obtaining fresh water, which leads to the conclusion that construction of a desalinization plant should be a last resort, after all other attempts at developing water have failed. Cost of the distillation plant will include:

1. Land for present and future expansion,
2. Construction facilities for roads, houses, etc.,
3. Plant construction including the structural and mechanical parts,
4. Fuels used,
5. Operating and maintenance costs,
6. Costs of storage.

There will be a capital cost even before any kind of production begins. After production begins, there will be a relation between production and costs. Distillation is a vital source of water in dry areas. Special interest should be presented for the construction and use of a dual or conventional plant. The location of the plant might be a pivoting variable on which the cost will vary. Any factor which would effect the production should be evaluated. There are many factors which will determine the cost of distilled water. Some of the costs are intangible though the evaluation should be as factual as possible. The complexity of the different variables might force the elimination of some components and consideration will be for those which are locally applicable.

Underground Brackish Water. The cost of brackish water production is considerably less than the distilled water, nevertheless it should be carefully studied as a possible source in solving water shortage. The cost must include the following items:

1. The cost of drilling and pumping out the water,

2. The cost of operation and maintaining the pumping machines,

3. The cost of conveying, operating and maintaining the system,

4. The cost of treating when needed,

5. The cost of the water after mixing it with other sources of water,

6. The cost of storage.

Underground Fresh Water. If there is enough fresh water in the needed area, it might not be necessary to produce distilled water, or if distilled water is needed, it might be in a limited quantity. If the final decision is to build a distillation plant, there are two possible solutions for the sweet ground water. One is to leave the water in storage as a safety measure, since it is possible that the entire system might not work as intended. The other way would be to use the sweet water as soon as it can be made available to the consumer. The cost of the fresh water will not differ too much from the brackish water except for the possibility of having to drill more deep wells, particularly in dry countries, to secure the fresh water. The cost of the fresh ground water must be analyzed with all the factors mentioned above for the brackish water.

Effluent Water. If a water shortage developes, the effluent can be considered as one of the water sources. A properly designed sewage treatment plant can produce an effluent of an acceptable quality chemically and biologically. The consumers from the numicipal, industrial, and agricultural areas typically use the water one time only, but in almost every case it is possible to reduce the water consumption greatly by applying other methods of securing additional water sources such as water re-use. If the decision of using the effluent will be considered, the following costs must be accurately determined:

1. The cost of sewage treatment to produce water of a certain specified quality and quantity,

2. The cost of conveying, operating and maintaining the system,

3. The cost of the water after it has been mixed

with other kinds of water,

4. The cost of storage.

Benefit Function

Introduction. The benefit function has been defined as the amount of money, which the consumer is willing to pay. The benefits for irrigation purposes, or industry uses will be inputs to the principles of the market value. The benefits for municipal water supply, will be represented in the form of the cheapest cost. The benefit function may perform in one of two ways; the first is the exact benefit when the system is operating on a required and specified output. The second is a possible failure to meet the required demand, resulting in either a deficit or surplus in quantity.

In Figure 2-1, the horizontal axis represents output (quantity), and the vertical axis shows the benefit (dollars). For a required output (x,y), consider the following conditions;

1. The line A with a slope of 45° represents the system when operating on a required and specified output and no deficit or excessive output is produced.

2. The line A_1, with a slope more than slope B, represents a deficit in benefits.

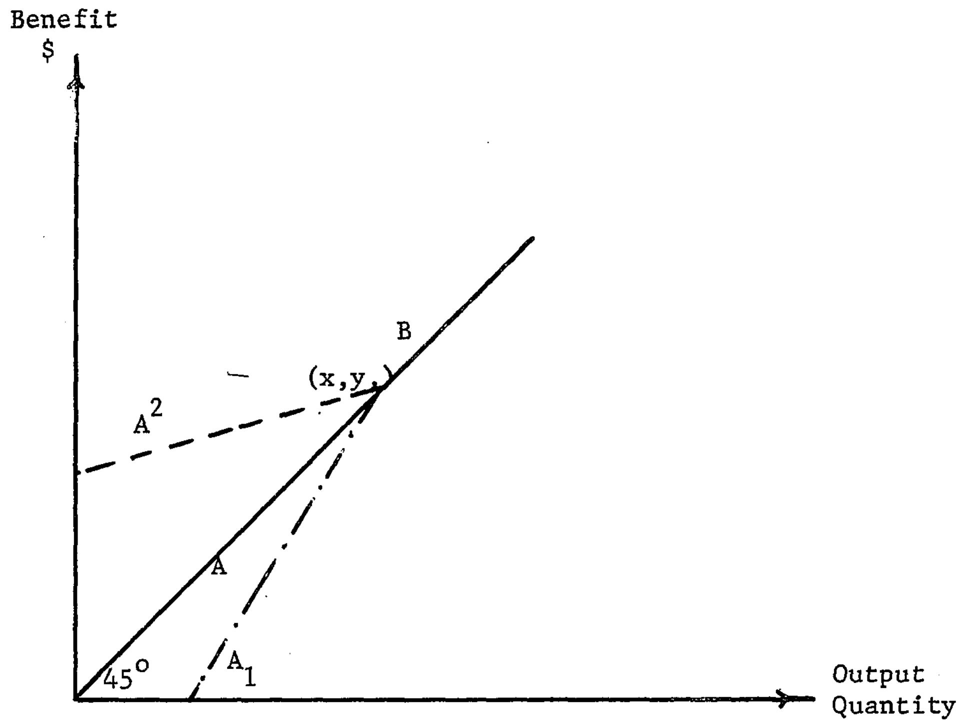

Figure 2-1

Benefit and out put functions

3. The line A_2, with a slope less than slope B, represents a surplus in benefits. (Maynard, 1966)

An economic loss is obvious when the system shows a deficit or excessive output is produced. To determine the optimal solution, benefits should measure the lesser of the two values: (1) the resource cost of providing equivalent goods and services by the least costly alternate means external to the system, where the alternate cost is measured on the same basis as system cost; (2) willingness of consumers to pay for the goods and services.

Municipal Benefit. In desert regions, four terms should be considered before constructing the benefit functions. They are quantity, quality, location, and time needed. Any kind of analysis will show that the benefit from municipal supply is extremely difficult to determine because there is no alternate commodity for drinking water. Since it represents a vital necessity for living and it is absolutely essential to life, it is not easy to represent it on a cost benefit basis because there is no top limit to the price; people are willing to pay for it.

Generally, it is a common practice to provide the quantity and quality needed from the cheapest sources of water supplies. The decision to provide adequate water for municipal purposes may be made without a prior benefit cost analysis. Municipal water needs have priority in the overall water resources development, especially in desert areas. (Kuiper, 1965)

Industrial Benefit. In a thorough evaluation of the benefits of water for industrial use, a precise determination of the following should be made:

1. Population growth and industrial development,
2. Power needs for industrial development,
3. Facilities for conveyance of water,
4. Marketing facilities and demands,
5. Cost, quantity, and quality of needed water,
6. Availability of technical personnel.

The cost of the establishment and development of water resources can be determined, and the benefit from an industrial development can be found. A more conclusive test is to determine the cost in terms of benefits for other purposes, such as agriculture, to provide a guideline for a possible increase in water used in industry. The benefit from an industrial development can be figured by providing less quantity required of water e. g., 75 per cent and increasing the quantity of water for agriculture. An increase in the agricultural output and a decrease in industrial production will provide a guideline for maximum utilization of water (Maynard, 1966).

Agricultural Benefit. Irrigation water supply profit should be measured both directly and indirectly. Direct profits include actual revenues. Indirect profits include long range farm and national development benefits. These benefits can be maximized by delivery of irrigation water on time where required.

Variables influencing successful irrigation practices include:

1. Land type,
2. Climate,
3. Farm sizes and distributions,
4. Crop types,
5. Marketing facilities and demands,
6. Short and long range effects of successful agriculture on the national economy,
7. Cost, quality and quantity of water used.

The willingness of the consumer to pay (direct profits) and the long range intangible benefits (farm and national development) determine the value of irrigation water. Direct irrigation benefits can be obtained by comparing the same farm incomes with and without the development of the irrigation project. Usually, the farmers' willingness to pay is considerably less than the increase in their income.

Most important, however, the water resource development, especially for irrigation purposes, is a vital factor in attracting new industrial and agricultural activities, which in turn create profitable economic and social growth.

Efficiency Function

It is necessary to find an optimum water resource development approach (for municipal, industrial and agricultural users) from among several feasible solutions. The optimum approach will demand the lowest costs and produce the greatest economic and social gains.

Economic evaluations of a development method must clearly present development and operations costs, and projected economic gains. In the Harvard Study in Design of Water Resources (1962) costs and benefits are weighed against the ultimate success or failure of the resource development problem objectives. Gross benefits E(A), represent consumer willingness to pay for a Design A; gross costs, C(A), indicate required selfdenial of goods and services by consumers to make possible the construction and operation of Design A; net benefits, E(A) - C(A), define the disparity between willingness to pay and the market values of displaced goods and services. If Design A output is defined as Vector Y = (Y , . . .Y), and its input as Vector X = (X , . . .X) its efficiency function will be

$$W(A) \doteq E(Y) - C(X)$$

in which outputs and inputs are related to each other by a production function (Mozayeny, 1963),

$$f(x,y) = 0.$$

However, the Harvard ranking function method is not applicable. For example, projects A and B may have gross benefits of 800 and 400, and gross costs of 300 and 100 respectively. Ranking function analysis yields

Project A	W(a) = 800 - 400 = 400 units
Project B	W(b) = 300 - 100 = 200 units

Project A shows more gross benefit than Project B. Obviously the analysis favors large projects. However, if investment return (benefit) rates are compared with costs, then

$$B(A) = \frac{W(A)}{C(A)} = \frac{400}{400} = 1$$

$$B(B) = \frac{W(B)}{C(B)} = \frac{200}{200} = 2$$

Project B now offers greater efficiency and more benefit to the country's economy. The maximum efficiency of Project B is represented by the intersection of marginal benefit and marginal cost curves, as explained in the next graph.

For the optimal design, the marginal benefit (the first derivative of the benefit), and the marginal cost (the first derivative of the cost) are equal, (Ecksten, 1958), e.g.,

$$\frac{MB}{MC} = 1 \quad \text{or} \quad \frac{d(\text{benefit})}{d(\text{output})} = \frac{d(\text{cost})}{d(\text{output})}$$

to assure the optimization to be maximum, the second derivative of the above equation must be negative, i.e.

$$\frac{d^2\ (\text{benefit})}{d\ (\text{output})^2} < \frac{d^2(\text{cost})}{d(\text{output})}$$

In Figure 2-2, the marginal revenue intersects the marginal cost in E. The distance Me represents the most efficient scale for the project. The area OMND presents the labor cost, DNLT presents the total profit, PLT presents the surplus, and the area bounded by PLMO presents the willingness to pay for a specified quantity M.

Reid (1967) discussed the concepts of economic efficiency versus welfare economics in the following statement:

> "The first place the benefit evaluation is used in the water resource development program is in project formulation.
>
> The objective of project formulation is to develop projects in such a manner as to result in the maximum excess of benefits over costs. There are four steps involved in this process. The first is the selection of the core of the project and addition of separable segments of that core to the point where the benefits just equal the costs. The second step is the selection of other functions and the addition of them to their marginal point. The third step involves a check to be sure that no function could have been served more cheaply through single-purpose alternative means, and the final step involves a check to be sure that the storage space or water or whatever the project is intended to provide will be used for the function of functions that will result in the greatest benefit.
>
> The second way benefits are used in the analysis is in the justification of any proposed development. A benefit-cost analysis is made to determine whether or not the benefits exceed the cost and whether the proposal is justified.
>
> A third place the benefit evaluation is used is in the cost allocation. While demand, supply, and price do not exist in the public section. . . economic concept of demand, supply and price are useful tools in describing the procedures."

The benefits of water resource development projects in desert areas should be stated in terms of their contribution to the development goals of the economy, including their intangible effects on the society. The so-

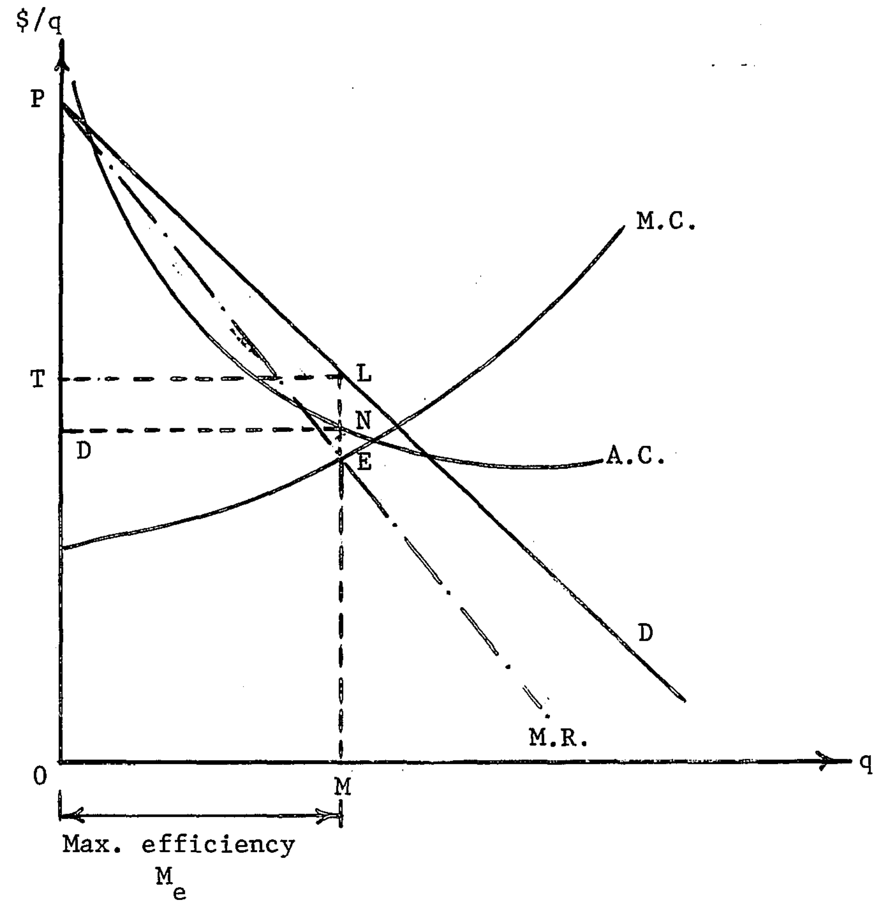

Figure 2-2

Marginal cost, marginal revenue
and maximum efficiency

ciety must define and observe limitations of its agricultural production and industrial development in terms of the available water supply. However, due to the difficulty of representing the intangible effects of a water resource development project in a desert area, it is replaced in a mathematical model by the minimum production cost. Establishment of the minimum production cost requires that all components affecting price should be represented, each carefully analyzed, and will be shown in Chapter V.

CHAPTER III

OPTIMIZATION THEORY AND WATER RESOURCE PROBLEMS

A scientific model is a representation used to predict and control data which define the limits of a complex problem. Manipulation of problem variables may cause irreversible results, but model components can safely be varied to help determine the optimum solution of a problem.

Three types of models will be considered here: iconic, analogue, and symbolic.

Iconic models are metrically scaled representations of either dynamic or static problem states at a specific moment. They are designed to establish the basic characteristics of a problem and use such techniques as photographs and flow charts.

Analogue models represent a sequence or sequences of dynamic conditions by substituting arbitrarily chosen properties for those in a problem. Analogue models, such as graphs, are structurally less specific than iconic models.

Symbolic models represent a physical system, or a set of linear or non-linear relationships between variables, either measurable or not, subject to inequalities or constraints. These models predict the behavior of a system under various conditions of planning and operation. Two types of symbolic models are utilized; (1) Deterministic models such as unit hydrographs, ignoring data uncertainties, and (2) Stochastic models, considering data uncertainties, such as the occurrance of floods and rain storms (Reid, 1966).

Optimization Theory Background

Euclid, in the third century B. C., included the first known published optimization theory problems as part of his thirteen-volume geometry treatise, Elements. However, almost 2000 years passed before such mathematical disciplines as infinitesimal calculus (Leibnitz, 1646-1716 and Newton, 1642-1727) and calculus of variations (Jacob Bernoulli, 1654-1705 and John Bernoulli, 1667-1748) were developed capable of rigorously defining optimization problem solutions (Russell, 1961).

Reid, (1967), summarizes the different optimization techniques as follows:

1. (1847) Couchy's steepest ascent
   (1947) Dantzig linear programming
   (1950) Bellman's dynamic programming

2. Unimodality--where there is only one maximum in an interval.

3. Level Contours, Peaks, Saddles--concept of multi-model.

4. Interval of Uncertainty--assume interval X_1, X_2 with $Y_1(X_1)$ and $Y_2(X_2)$, if $Y_{max}(X^*)$ is between X_1 and X_2, exact location not known, interval of uncertainty.

5. Minimax Principle--to minimax worst outcome. So in selecting new sub-division--take mid point.

6. Optimization--without constraints--two variables.

   New interval
   of uncertainty

   $$I_1 = X_{j+1} - X_{j-1}$$

   in terms of <u>n</u> trials

   $$I_1 = \frac{2I_0}{n+1}$$

   So use exhaustive search.

7. Dichotomous Search

   $$I_K = \frac{I}{2^K} + \left(1 - \frac{1}{2^K}\right) E$$

   K^{th} interval of uncertainty
   I_K length of K^{th}

   E separation

8. Equal-interval (E) Multi-Point Search

$I_K = (2/3)^K I_0$ (2 points)

$I_K = (1/2)^K I_0$ (3 points)

so more point, great shrinkage

9. Others-non-equal, by Fibonacci and Golden

10. Optimization, without constraints--several variables

11. Exhaustive Search

$$\eta = \prod_{i=1}^{r} \frac{2I_0}{I_{1i}} - 1$$

r = variables

i^{th} variable

12. Random Search--select at random, and save the highest

for n trials

s = probability in subregion

a = subregion

$s = 1 - (1-a)^n$

$$n = \frac{\log (1-s)}{\log (1-a)}$$

(so for probability 0.9, that one will be in a, of size 0.01, it will take 230 trials (n))

$$a = \prod_{i=1}^{r} \frac{I_{1i}}{I_{0i}}$$

(if r = s, reduce to 0.2 of original area, at 0.9 probability, n = 7,142)

13. Univariate Search--all but one variant are held fixed--and a maximum sought--then repeat for all. Then repeat.

14. Direct Search--exploratory move, pattern move

Move AX and then continue if improved, other-wise move -AX, etc.

15. Optimization Steepest Descent

$$S^K = \left| \frac{\overline{\ \ K\ \ }}{\dfrac{-g^{\ K}}{g}} \right|$$

X_0 is starting point, direction is in negative gradient.

$\overline{\ \ K}$
g is gradient at $\overline{X}^{K}$ new station

$$X^{K+1} = X^K + \alpha_K \overline{\ \ K}_S$$

α_K is dist. moved.

16. Optimization with constraints--linear

Linear programming Max

$$Z = \sum_{j=1}^{r} C_j X_j$$

Subj

$$\sum_{j=1}^{r} a_j x_j (\leq = \geq) b_j \quad i=i$$

17. Optimization with Constraints--non-linear
Lagrangian multipliers
Cutting plane method
Gradient projection
Dynamic programming

18. Macroscopit Approaches

19. Sensitivity Analysis--evaluates importance of variation to objective function.

Modern business, industry and government complexes commonly develop allocation problems. Limited progress has been made in development of optimum techniques for solving these problems, but mathematical programming shows the most promise. Allocation problems usually contain large groups of variable sub-units. Their study is characterized by the necessity for optimal solutions in terms of the external interests of the complete organization (Churchman, 1957).

More simply, allocation problems arise when (1) several methods may be used to perform a number of activities and (2) resources are not available for performing each activity in the most effective manner. Thus, optimum solustions to allocation problems arequire that activities and resources be combined in the most effective manner.

Mathematically, allocation problems maximize the effectiveness of a given function, subject to a given set of restrictions, such that values of x_1 maximize

$$z = f\ (x_1,\ x_2\ ,\ .\ .\ .\ x_n)$$

subject to

$$g_1\ (x_1,\ x_2,\ .\ .\ .\ x_n) = 0 \quad i = (1,2,...m)$$

$$x_j \geq 0 \quad j = (1,2,...n)$$

In contrast to the general allocation problems, those limited to linear effectiveness functions (to be maximized or minimized) and linear restrictions have been solved with significant success and will be used in this paper.

Mathematical Model

Both mathematicians and economists have expressed interest in linear programming for about fifty years, and specific literature dates from the 1920's. Following Dr. George B. Dantzig's first published paper on the simplex method in 1947, development of the field has been rapid.

"Linear programming" generally refers to any method establishing the point at which a given linear function of several variables approaches an extreme value, its configuration, non-negative variable requirements, and linear equality or inequaly restraints. (Liewllyn, 1966)

After isolating the problem and its solution requirements, the engineer generates a design concept, usually as a rough configuration of the desired system or process. Next, he attempts to "model" the object system or process. This model may assume a wide variety of forms, as already discussed, but mathematical types usually are preferred.

The mathematical model normally contains N parameters which will be called the design variables, x_1, x_2, x_n. In the design vector $\overline{X} = (x_1, x_2, \ldots x_n)$ each design variable is a point in the space containing all of the design variables. It may happen that certain equality constraints

$$g_{,} (\overline{x}) = 0 \ldots g (\overline{x}) = 0$$

and/or inequality constraints

$$g_{\pi+1} (\overline{x}) \leq 0 \ldots g \overline{x}_{g}$$

are imposed on the space, allowing only points in a portion of the total space to be considered as acceptable candidates for solution of the design problem. This region is called a feasible space, or a feasible solution.

Equality constraints result from given exact functional relationships among the N variables. If values of some of the design variables may be changed, then π must be smaller than N.

Inequality constraints usually result from a specified design limitation. There is no upper limit on the value of π.

When using a mathematical optimization technique to find the "best" design, a meaningful, computable, quantitative, single-valued function of the design variables must be formulated to serve as a control for comparison and a measuring stick of the feasibility of design choices. This usually is called the objective function.

Water Resources and Mathematical Models

Water resources planning and development use of operations research has developed during the last decade. Two analysis approaches are used. The system may be simulated in a high speed digital computer, and the best combination of variables selected by observing responses of the simulated system to variable combinations or, mathematical models may be used to solve directly for an optimal design. The latter approach will be used in this paper to develop a model providing for optimal use of water resources in an arid area.

The problem will be formulated both through an analysis of the principal phases of the system and possible control methods. Next, a model will be constructed to test the effectiveness of the system, expressed as a function of the values of the variables which define the system. Some of these variables may be changed to define alternate courses of action. Others will represent system demands and cannot be changed.

The measurement of the effectiveness will be represented by η, X_i represents variables which can be changed, and Y_j represents demands which are constant. The general equation of the model will be

$$\eta = f\ (X_i,\ Y_j).$$

Initially, all system components will be analyzed which contribute to its effective operation. Next, the maximum effect of each of these components will be grouped, and analyzed to determine the demands or variability of each group. If the group is variable, those aspects of the system which contribute most to its deviation will be found. After each variable or fixed component has been analyzed, a symbol will be assigned to each subcomponent.

In Chapter II, a full analysis for the components of the whole system was given. There were four sources of water which will be indicated by X_1 (distilled water), X_2 (underground fresh water), X_3 (underground brackish water), and X_4 (effluent). Each has subcomponents which affect its cost, which can be represented by $a_1, a_2, \ldots a_n$. The unit cost y of the four sources (X_1, X_2, X_3, and X_4) will be equal to

$$Y = a_1X_1 + a_2X_2 + a_3X_3 + a_4X_4.$$

The value of a_i will be evaluated in terms of dollars, and will depend on the different factors given in Chapter II. The mathematical model can be represented by the following matrix.

	X_1	X_2	X_3	X_4
Y_1	a_{11}	a_{12}	a_{13}	a_{14}
Y_2	a_{21}	a_{22}	a_{23}	a_{24}
Y_3	a_{31}	a_{32}	a_{33}	a_{34}
Y_4	a_{41}	a_{42}	a_{43}	a_{44}
Y_5	a_{51}	a_{52}	a_{53}	a_{54}
Y_6	a_{61}	a_{62}	a_{63}	a_{64}
Y_7	a_{71}	a_{72}	a_{73}	a_{74}

Herein, the variables which will be considered are summarized and grouped into seven, consequently, the unit cost y will be represented seven time. The optimal solution will be the minimum cost of Y from the above seven Y's. To find Y, the system will be presented by a set of equations which define the relationship between the system variabiles parameters, constraints, and demands.

The mathematical forms of the model may vary. Consequently, the mathematical analysis for deriving a solution also may vary. Because the design of a water-resource system for arid or semi-arid areas is complex, drastic simplification is required. Mathematical programming methods are pertinent for this model because many of the operation restrictions on the water resource system are linear.

If a system is fed by four sources in parallel, the following kind of constraint will arise:

> quantity of water from source number one plus the quantity of water from source number two plus the quantity of water from source number three plus the quantity of water from source number four must be greater than or equal to the total quantity of water required.

Constraints of this type can be analyzed by a mathematical program to determine optimal operating decisions and unique solutions. The water resources problem in desert regions can be represented in the following model:

Source	Capacity		Production				Cost			
	Min.	Max.	1	2	3	N	1	2	3	N
X_1	X_{11}	X_{1N}	X_{11}	X_{12}	X_{13}	X_{1N}	C_{11}	C_{12}	C_{13}	C_{1N}
X_2	X_{21}	X_{2N}	X_{21}	X_{22}	X_{23}	X_{2N}	C_{21}	C_{22}	C_{23}	C_{2N}
X_3	X_{31}	X_{3N}	X_{31}	X_{32}	X_{33}	X_{3N}	C_{31}	C_{32}	C_{33}	C_{3N}
X_4	X_{41}	X_{4N}	X_{41}	X_{42}	X_{43}	X_{4N}	C_{41}	C_{42}	C_{43}	C_{4N}

The production stages represent different suggested capacities associated with specific cost.

The total cost $Y_1, Y_2, \ldots Y_n$ will be equal to the total production of each source and must be determined to insure maximum output with minimum cost, if the demands must be satisfied with limited resources. X_{ij} represents the capacity of the resources (i) which should satisfy the demands (j). Now the problem is reduced to minimizing the linear form.

$$Z_1 = C_{11}X_{11} + C_{21}X_{21} + C_{31}X_{31} + C_{41}X_{41}$$

$$Z_2 = C_{12}X_{12} + C_{22}X_{22} + C_{32}X_{32} + C_{42}X_{42}$$

$$Z_3 = C_{13}X_{13} + C_{23}X_{23} + C_{33}X_{33} + C_{43}X_{43}$$

$$Z_N = C_{1N}X_{1N} + C_{2N}X_{2N} + C_{3N}X_{3N} + C_{4N}X_{4N}$$

subject to the constraints

$$X_{11} \leq X_{11}, X_{12}, X_{13}, X_{1N} \leq X_{1N}$$

$$X_{21} \leq X_{21}, X_{22}, X_{23}, X_{2N} \leq X_{2N}$$

$$X_{31} \leq X_{31}, X_{32}, X_{33}, X_{3N} \leq X_{3N}$$

$$X_{41} \leq X_{41}, X_{42}, X_{43}, X_{4N} \leq X_{4N}$$

and

$$X_{1N} + X_{2N} \geq R_1$$

$$X_{3N} + X_{4N} \geq R_2$$

$$X_{1N} + N_{2N} + X_{3N} + X_{4N} \geq R$$

where R is the total quantity of water needed for domestic and non domestic uses, R_1 is the total quantity of water required to satisfy the domestic needs, and R_2 is the total quantity of water for agriculture and industrial uses.

The solution of such model will be represented in Chapter IV.

CHAPTER IV

WATER RESOURCES IN THE STATE OF KUWAIT

Introduction

Kuwait is on the northwestern shore of the Arabian Gulf, between latitudes 28^{o} 45' and 30^{o} 5' north and longitude 46^{o} 30' and 48^{o} 30'. The country is bordered on the north and west by Iraq and on the south by Saudia Arabia and a "neutral zone." The land area of Kuwait is 6000 square miles and is almost rectangular in shape. The State is about 110 miles from east to west at the widest part and about 88 miles from south to north in a straight line from the Neutral Zone to the northern border. Largely a desert, except for the Jahra oasis and a few fertail patches in the southern and coastal areas, Kuwait has no natural water resources.

The coastal plain of Kuwait is low and flat. The eastern part of the State is very similar with most of the prominent hills reaching a height of only 660 feet. Dry wadis break the pattern of the plateau in the west. A gradual rise in elevation in the west reaches about 1000 feet. The western plateau slopes toward the northeast with an average rise of about 1:500.

The formation of the Kuwait group consists of the Didibba Fars formation and the Ghar formation. Sediments, mainly wind-blown sand and coarse gravel, become exposed at ground level over a large part of northern Kuwait. Such sediment, of a relatively recent age, merges below with sand and gravel of the Didibba formation. The Didibba rocks are dominantly cemented sand, gravel and sils with a small amount of clay. The rocks are known locally as sandstones, conglometric sand stones, and silt stones. The Lower Fars and Ghar formations consist of sandstone, limestone, shale, and variegated calcareous siltstone beds (Vattenbyggnads-byran, 1965).

The climate in Kuwait is extremely hot and dry in the summer and mild to cool in the winter when most of the rainfall occurs. A record of the monthly precipitation in Kuwait for the years 1956 to 1965 is shown in Table I. (Appendix A). The rainfall in the winter is caused mostly by continental fronts traveling from the northwest to the southeast. Precipitation, in addition to being low, is variable. There was 1.1 inches recorded in 1964 and 6 inches in 1957 (Planning Board, 1966).

During 1955-1962 the relative humidity in Kuwait varied from a mean daily average of 68 per cent in December to 26 per cent in June. Records show that the rate of evaporation per day varies between 1.2 inches in December and January to 7 inches in June and July. The total evaporation is about 141.2 inches per year or about 28 times the average rainfall.

The People

The lack of economic opportunities before the oil era, stimulated the Kuwaities to attain proficiency in marine, pearling, fishing, and boat building industries. (Ministry of Guidance, 1963).

Official information is lacking as to the population of Kuwait until the first census in 1957. In 1900, Kuwait was reported to have 10,000 and 12,000 population which would be only a little more than the total population in the eighteenth century. Ten years later there was a population of 35,000 and in 1937 the population was 57,000. The oil boom in the early 1950's accelerated population growth. Immigration, a high birth rate, and a decreasing death rate resulting from better health standards have produced an abnormally high rate of growth since 1957 when the first census was made. The census in 1961 showed a population of 321,621, and the April 1965 census totalled 467,339 as shown in Table II.

History of the Water Resources in Kuwait

Settlers in Kuwait had to bring their water from Shat Al-Arab in the southern part of the State of Iraq. The immigrants carried their water in water-dhows, and some of it was poured into a reservoir built on the shore and then sold. This water supply was certainly not free from impurities. The arrival of the water-dhows depended a great deal on weather conditions. However, this method of securing water did not change until the discovery and production of oil in Kuwait which brought sweeping changes in the country's way of life (Ministry of Guidance, 1963).

The State became the center of great enterprise which required scores of experts and thousands of workers. The population jump from 10,000 in 1910 to 467,339 in 1965 drastically increased the need for water. Every possible source was studied, first, the distillation of sea water, second, the brackish ground water, and third, ground fresh water.

Distilled Sea Water. In 1951 arrangements were made with the Kuwait Oil Company for an interim supply of distilled sea water. Pipes were laid from Ahmadi to Kuwait City a distance of about 18 miles, and 96,000 gallons of distilled water began to arrive each day (Witteny, 1965).

In Kuwait City the Shuwaikh Distillation Plant began operation in March, 1953, with a capacity output of 1 m.g.d. In February, 1955, another set of ten distillation units with a total capacity of 1 m.g.d. was completed. Extension of the plant and increased production ensued, and in March, 1958, the capacity of the plant increased by 2 m.g.d. In the summer of 1960 another distillation plant was commissioned with a capacity output of 2 m.g.d. Five m.g.d. plants were under construction in 1965 raising the total future output, when completed to 1486, (United Nations 1965) also shown in Table III.

Underground Brackish Water. Distilled water is so pure that it is tasteless. To make the water potable it is mixed with five to seven per cent of brackish water containing from 3000 to 4500 ppm. Such water is usable and of value for agricultural and industrial purposes, and its use reduces greatly the demand on sweet water.

In 1951 the brackish water field was located 9 miles southwest of Kuwait City and was piped to the city. The ultimate capacity of the field was about 18 m.g.d. The removal of the brackish water from this field from 1964 was about 18 m.g.d. Production from 1954 to 1965 is shown in Table VII.

Underground Fresh Water. Underground fresh water was found in May, 1960, in the northern part of Kuwait, following a survey of ground water potential made by the Parsons Corporation of Los Angeles. Their report showed that not more than 20,900 m.g. could be available for storage in the aquifier in the Rawdatain area (see map, page 62). The Parsons Corporation reported that the recovery of natural recharge would be 7 m.g.d. with 4 m.g.d. potentially available from artificial recharge. Estimates showed that the field could pump an average daily volume of 4 m.g.d. for a period of 20 years. Withdrawal rates of more than 5 m.g.d. would be possible for peak load demands. The Rawdatain water development brought water to Kuwait City in September, 1962.

Near Rawdatain the Um Al Aish water field was discovered during the survey by the Parsons Corporation. An estimated 19,000 m.g. of usable water became available from storage in the aquifier. The permeability of the strata forming the aquifier was less than the Rawdatain basin. The field could pump an estimated 2 m.g.d. for 20 years, but pumping could be increased to about 2.2 m.g.d. to meet peak demands. The Umm al Aish field was developed, and the ultimate capacity of the field is about 2 m.g.d. Consumption of ground fresh water from 1962 to 1967 is shown in Table XI, (Vattenbyggnadsbyran, 1965).

Present Water Sources

The distillation plant at Shuwaikh is connected both in design and construction to the power stations. The source of energy is natural gas piped from the oil fields. Sea water with a salt content of 4.3 per cent is pumped to the distillation plants, and fresh water is produced. The water is treated with chlorine to prevent the growth of marine life in the pipes and tanks. After such treatment the water passes through filters before flowing to the distillation units.

From the distillation plant at Shuwaikh the water is pumped through two 18" and one 12" pipelines of asbestos cement to ground level tanks at Shuwaikh. The water in the ground level tanks is mixed with brackish ground water to produce a desirable taste, see Table IV. Then the water flows to six water towers, see Table V. The towers pipe the water to 14 distribution stations where water can be piped directly to tank trucks as shown in Table VI, which make house-to-house delivery.

The brackish ground waters reach Kuwait through a network of pipelines which branch out to form a three million gallon reservoir in Sulaibiyah. The water is then piped from the Sulaibiyah reservoir to many tanks in the Shuwaikh area which are about 80 feet lower than the reservoir. From Shuwaikh, the water is pumped to various distribution areas and to the tanks of Hawalli which are 40 feet lower than the Shuwaikh tanks. Four asbestos pipelines carry the water from the Sulaibiyah reservoir. Storage tanks for brackish ground water are shown in Table VIII. Brackish water towers are shown in Table VI, and brackish ground water distribution stations are shown in Table X.

At this time, there is no suitable source of water of enough quantity so that it can be used solely for agricultural purposes. Part of the brackish ground water is used for agriculture, for watering public parks, private gardens, and public trees along the streets.

In the Rawdatain water field 25 production wells have been drilled. The water is surfaced by deep well pumps. A system of asbestos cement pipelines has been built to a 7.5 m.g. ground level reservoir in the southern part of the field. Twenty-six production wells have been drilled in the Umm al Aish water field. Water from this field is brought by deep well pumps, through a system of asbestos cement pipelines, to the Rawdatain ground level. From Rawdatain the water is sent by the main pumping station through a 24" steel water main to Mutla. From Mutla the water flows by gravity through a 26" steel water main to the ground level reservoirs at Shuwaikh. The pipelines from Rawdatain to Hutla are 32 miles long and those from Mutla to Shuwaikh 20 miles, see Figure 4-1 (Vattenbyggnadsbyran, 1965).

Present Water Production Costs

Water production costs reported by the Ministry of Electricity for March, 1965 are given in the following:

Distilled Water Production Costs

(These costs are based on an average production of about 4.4 m.g.d.)

Capital costs	238 fils
Operation costs	207
Maintenance	121
Overhead	41
Total	607 fils = $1.7

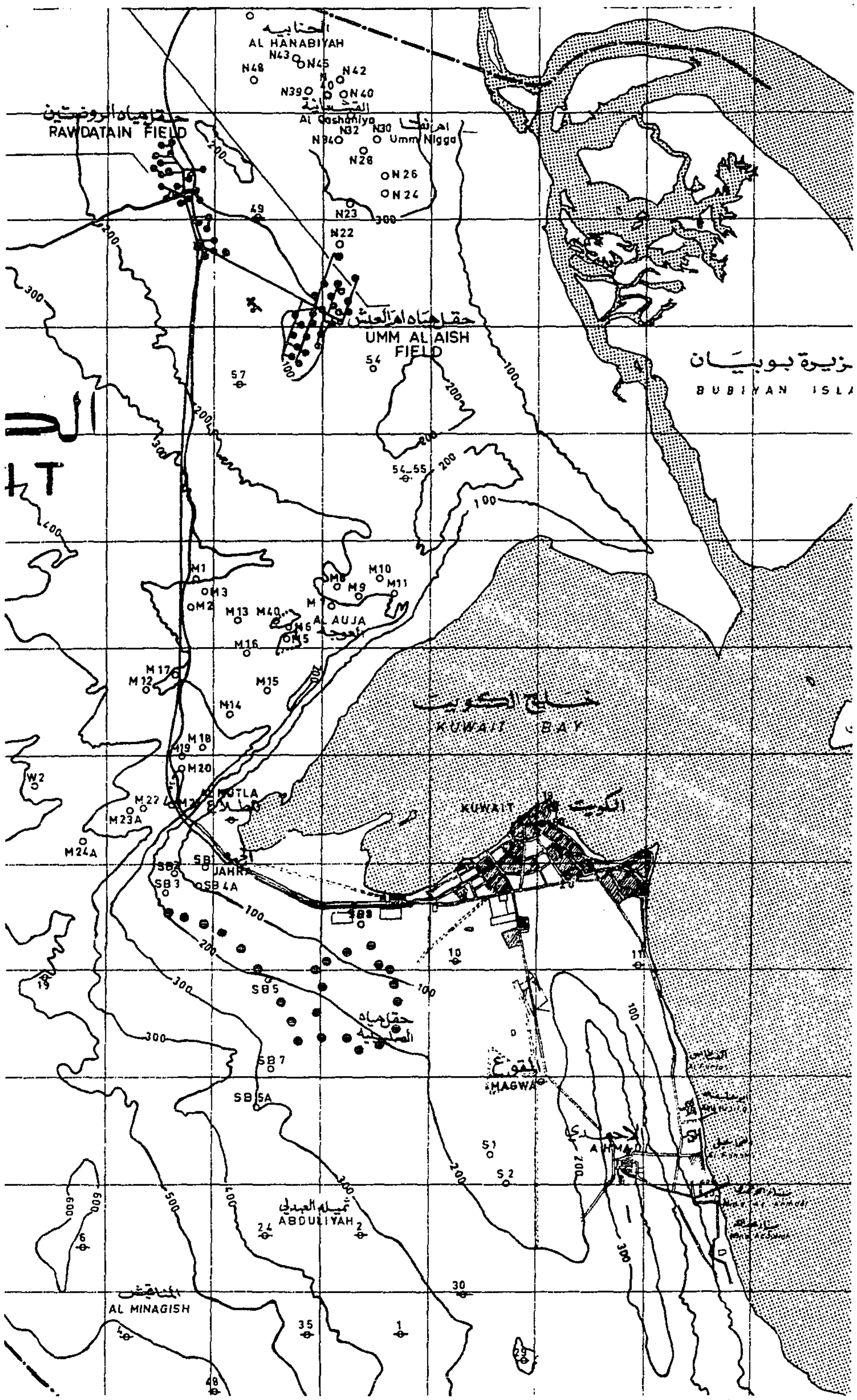

Figure 4-1

State of Kuwait and Its Water Sources

Underground Brackish Water Production Costs

(These costs are indicated without giving the information on which the production costs were calculated.)

Capital costs	73 fils
Operation costs	8
Maintenance	13
Overhead	5
Total	99 fils = $.27

Underground Fresh Water Production Costs

(These costs are based on an average production of about 2.2 m.g.d.)

Capital costs	181 fils
Operation costs	52
Maintenance	19
Overhead	11
Total	263 fils = $.73

The rates at which water may be brought by consumers are as follows:

Fresh water at distribution systems	500 fils
Fresh water transported by tankers	1500 fils
Brackish water at distribution station	free

Water Needs in the Near Future (1972)

Future population trends are very difficult to predict as Kuwait is still in a period of economic expansion and probably will remain so in the forseeable future (Metcalf, 1965). High birth rates can be expected to continue for the next 20 to 30 years with only a slight reduction probable after 30 years. Immigration and emigration are major factors in population forecases. The great educational programs now being conducted will create an increasing number of skilled Kuwaitis who can take over many jobs now being held by non-Kuwaitis. The rapidly expanding economy, with its demands for more services, will create much employment that can only be filled by bringing people to Kuwait. The non-Kuwaiti population will increase, but present plans acknowledge that it will be at a rate less than the Kuwaiti population.

The expressed aim of the government of Kuwait is to provide employment opportunities for an increasing population. Increased industrialization will provide much of the needed employment. To date, the economy of the State has been based upon the great oil reserves, the large construction programs, and the necessarily large import business required to support the people. Construction should continue but eventually at a slower rate. Some of the increasing population will need to find employment in new fields. Kuwait imports almost all of needed products so a variety of small industries will probably develop. Growth in light industry, assembly type industry and service industry, will create additional demand for water. Many other factors will affect the rate of growth of the population in the future.

A high and low population growth curve is necessary because of the difficulty of accurate predictions for more than a few years. The lower projection is based on a compounded or geometric rate of increase for three per cent per year for the Kuwaiti population and two per cent for the non-Kuwaitis. In addition to previously discussed factors affecting the population, some of the non-Kuwaitis probably will emigrate each year. This emigration will partially offset the natural increase in population because of the high birth rate (Metcalf, 1965).

The 1965 population was 220,000 Kuwaitis and 248,000 non-Kuwaitis with a total population in A.D. 2000 will be 620,000 Kuwaitis and 499,000 for non-Kuwaitis, totaling 1,119,000 people. The higher projection is based on the rate of three and one-half and two and one-half per cent increase. The Kuwaiti population is estimated to grow from 200,000 in 1965 to 735,000 in the year 2000. The non-Kuwaiti population should increase from 248,000 in 1965 to 590,000 in 2000. The higher projection predicts 20 per cent more growth than the lower projection. An "average curve" midway between the two projections has been computed and is shown in Table XII. (Vattenbyggnads-byran, 1965) consultant engineer, suggests that the population by the year 2000 will be 700,000 persons. An estimate of 1,000,000 persons will be considered for the design criteria and the necessary economic analysis.

The major part of the present population of Kuwait is located in Kuwait City, its surrounding suburbs, Ahmadi, the port and industrial complexes, and along the coastline between Kuwait City and Ahmadi. Future population growth should be in this area, and also, in the triangle of land formed by Jahra, Kuwait City, and Ahmadi. Planned residential developments have been tentatively set for this area. Future industrial development is likely to expand in the same area. Figure 4-2 shows the population and water consumption from the present time until 2000.

The usual basis for estimating future water requirements is the record of past consumption, affected by the following factors:

First, water has been delivered by tanker trucks, which is a relatively expensive means.

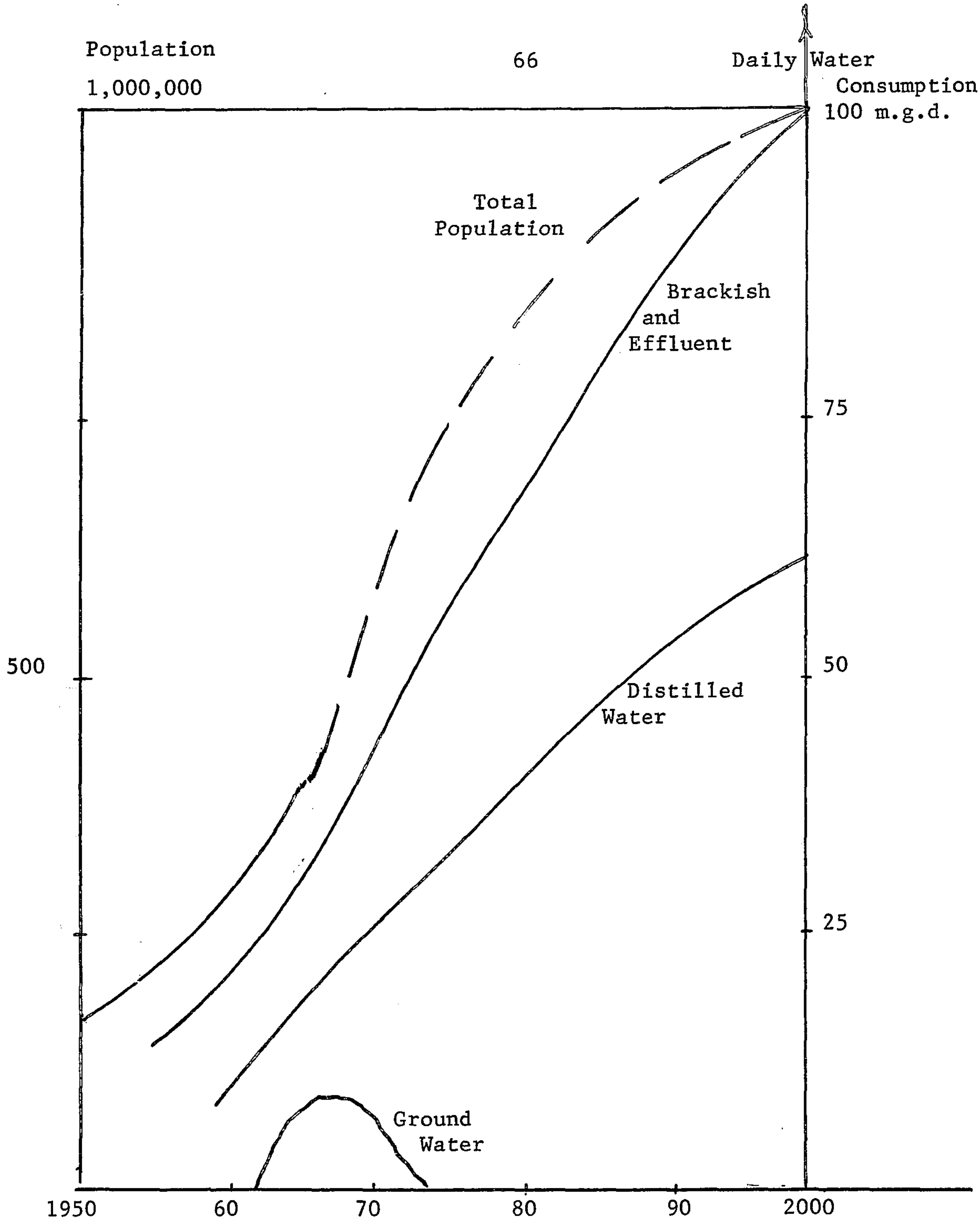

Figure 4-2

Population and Water Resources Present and Future

Second, due to the limited supply of fresh water, brackish water is utilized in many ways other than drinking.

Third, increased standards of living and higher wages will increase consumption of water.

As the economy expands, so will the use of water. This is true particularly when an increasing part of the urban population has immigrated from areas where water has been historically more available. Increased health standards will account for some of the increased use of water. Estimates by the officials agree that 1970 will be the time when the suggested integrated system will be in complete operation. Now the fresh water and brackish water demands, averaged for this year, are approximately 20 gpcd and 32 gpcd respectively.

The greater availability and lower cost of water will increase the consumption of the potable domestic water. This increase is expected to be 15 gpcd, bringing the total domestic water demand to 35 gpcd and the brackish water to 72 mgpd. The use of nonpotable water during this period will be limited by the capacity of the brackish water wells and the sewage effluent. Expansion of agriculture can be solved with sewage effluent, a valuable water resource when used with other sources of water.

A sewage treatment plant for Kuwait City is now under construction. The plant is located southwest of the city, about 4 km west of Farawaniyah, and 2.5 km south of the Fourth Ring Road. The plant is designed for primary and secondary treatment, according to the activated sludge method. The effluent will be a source of moisture for irrigation purposes. The plant has a designed capacity of 22.5 m.g.d. The average water supply, which can be available for irrigation purposes, will be 67 per cent of the designed capacity. About 15 m.g.d. will be available for re-use. When the suggested integrated system is completed, with consumption of 60 mgd, the sewage flow from the city will increase in the same amount. Additional water supply available for reuse is estimated to be about 33 mgd. (Vattenbyggnadsbyran, 1965).

Water Resource Planning and Design

Water resources can be effecitvely developed to meet present and future needs of an area only following complete planning and design studies.

Planning

Water resource development planning requires the compilation of diverse basic data outlining prospective engineering designs, economic considerations and consumer needs. As already noted, Kuwait's population is expected to be 1,000,000 by A.D.2000. Presently, there are 28 districts in Kuwait and government municipal planning maps project an increase to 40 districts by A. D. 2000. Population and water needs for each of the new districts according to the maps are presented in Table XIII (Fozan, 1968). A dual water distribution system will be necessary to provide these areas with both fresh and brackish water to satisfy their domestic, industrial and irrigation needs. The Kuwait Planning Board has set a plan for producing 42 m.g.d. by 1972. It is suggested that Kuwait's needs will increase to 60 m.g.d. by A. D. 2000. This goal will be met by increasing the capacities of existing plants at Al-Shuwaikh and Al-Shuaibeh from 13 m.g.d. and .50 m.g.d. to 32.30 m.g.d. and 27.70 m.g.d. respectively as shown in Table XIV and XV. The Board also has set a brackish water processing goal of 75 m.g.d. by 1972. It is estimated that this should be increased to 100 m.g.d. by A.D. 2000 to satisfy increasing industrial and irrigation needs.

Presently there are a total of four ground-level brackish water storage tanks at Al-Shuwaikh, Hawalli and Sulaibiyah, here labeled A, B, C, and D, with capacities of 20, 20, 12, and 48 m.g.d. respectively. The brackish water storage tank D, with a capacity of 48 m.g.d. is located at Al-Shuaibeh, an area of heavy industry as shown in Table XVII, XVIII, XIX, and XX. The above plan should serve the long range interests of Kuwait in the most practical manner and with maximum benefits, providing optimum use of all presently available, potential water resources and storage tanks.

Design

Water may be conveyed by highway tank trucks, pipelines, siphons, canals, railroad tank cars, and ocean tanker vessels. Each has characteristic advantages and disadvantages. Only highway tank trucks and pipelines will be considered here. Capacities can be expanded gradually in a highway tank truck conveyance system by adding more units as peak demand grows. In addition, their radius of operation can easily be extended and has been shown the most economical conveyance technique for small quantities at relatively long distances, as shown in Figure 4-3 (Koenig, 1959). Water tank truck conveyance also is less

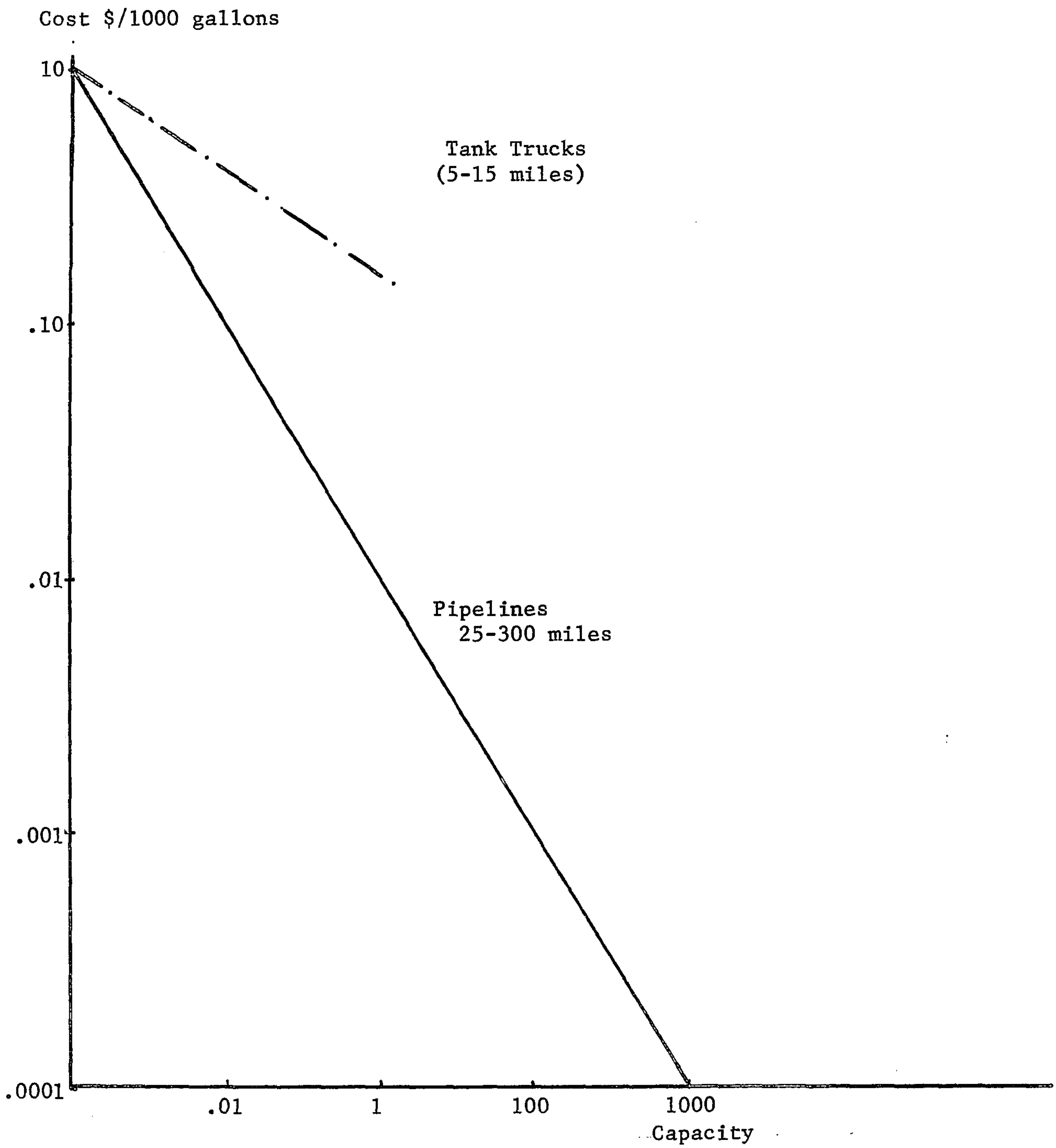

Figure 4-3

Conveyance of Water by Tank Trucks and Pipelines sensitive to seasonal temperature variations, provided all needed highways are available.

However, tank trucks have a load factor of only 50 per cent, since they must return empty. Other disadvantages include contamination hazards and gamming traffic.

In contrast, pipelines convey water with little probability of its contamination. Further, they can easily be designed for almost any capacity through appropriate pipe diameter choice, determined by current and estimated future demands, storage capacities at either end of the pipeline, utilization factors, pipe life and other economic factors.

Computer analysis of these distribution factors may be revised until an economical network plan is developed. All necessary hydrant locations, valves and separate pressure levels should be included in network plans. Storage capacities should be determined by evaluating the capacity of a developed water supply to meet hourly and daily demand peaks. Finally, storage facility costs should be compared with the alternative of increasing standby primary water supplies.

It has been suggested that a dual distribution water system be established in Kuwait; one network would convey potable water, the other would carry disinfected but other wise untreated non-potable water. The method of designing a water distribution system can be briefly summarized as follows: (Fair, 1965)

A. Input:

1. Make a layout of the system including building demands, pipe diameters and pipe length.

2. Identify each pipe in the system, and its position in the circuit.

3. According to the population and the area served by the circuit, assign an initial flow in each loop of the circuit.

4. Satisfy the condition $\sum Q = 0$.

5. Choose the appropriate diameter.

6. Find the velocity in each pipe and assume suitable C.

B. Output: The output will be the flow and the pressure head.

In Appendix B, full details for the necessary information for the design distribution system for the state of Kuwait are in tables A-D (XX), B-D (XXI), A-B (XXII), B-B (XXIII), C-B (XXIV), and D-B (XV), and the schematic diagrams in Figures 1(A-D), 2(B-D), 3(A-B), 4(B-B), 5(C-B) and G(D-B). A computer program written by Graves (Graves, 1961) and modified by the author is presented with its flow chart.

CHAPTER V

MATHEMATICAL MODEL FOR THE STATE OF KUWAIT

Kuwait presently has three sources of water: distilled, underground fresh, and underground brackish. Effluent water from sewage plants will be available in about the year 1970. Tank trucks deliver approximately 90 per cent of Kuwait's distilled water to consumers. Conveyance costs account for approximately 50 per cent of the consumer price. The Ministry of Electricity, Gas and Water (Ministry of Electricity, 1965) recently published the available data establishing water processing characteristics and costs for the three available sources in Kuwait.

Production Cost

Distilled water, according to the Ministry report, accounts for about 90 per cent of Kuwait's domestic water consumption. At present, it is the most expensive water processed for domestic uses. Yet it represents the main water resource in the country. Gas fuel to power distillation plants is domestically produced, and is supplied at no cost by the government. However, consumer costs do include charges for pipeline maintenance and distribution facility depreciation. The total government investment in distillation equipment and facilities in Kuwait is estimated by the Ministry report to be $16.78 million, and their operating costs is estimated to be $1,359,753. Also, 5 per cent capital amortization and interest brings the total annual cost of distilled water for Kuwait to $3,037,815. This cost reflects a total processing of 1,880,613,624 gallons, at an average unit production cost of $1.62 per 1,000 gallons (United Nations, 1964). The average consumer cost of almost $3.24 per 1,000 gallons is approximately twice the actual production cost, and includes distillation operations, equipment maintenance costs, chemical treatment, power, and 15-year equipment depreciation costs.

Underground brackish water processing does not require the same complex distillation plant facilities. For non-domestic and industrial uses, its cost, according to the Ministry report, is approximately $0.32 per 1,000 gallons, and for irrigation purposes about $.022 per 1,000 gallons. This includes surveying, drilling, reservoir construction, pumping station and pipeline costs to the distribution systems.

Underground fresh water resource development costs were estimated by the Ministry to be about $8.4 million, including surveying, drilling, reservoir construction, pumping station and pipeline costs to Kuwait City. The surveying, drilling and other activities associated with development of underground brackish water are also applicable to development of underground fresh sources. Fresh water delivery costs to Kuwait from the wells were estimated at $0.63 per 1,000 gallons.

For Kuwait, water conveyance costs constitute a substantial (50 per cent) percentage of the total unit cost paid by the consumer. It has been reported that transportation costs to consumers are about $1.64 per 1,000 gallons for distilled water from the distribution station to the consumer houses a distance of an average of 15 miles. The author has paid up to $1.40 per 1,000 gallons for brackish water conveyance by tank truck. Fresh water conveyance costs to public consumers are about $1.70 per 1,000 gallons.

As already mentioned, in the twenty-first century the needs of Kuwait are estimated at 60 m.g.d. for domestic uses and 1.00 m.g.d. for non-domestic uses. Unit processing cost could be reduced by about 30 per cent due to expanding water resource development (United Nations, 1964). The underground fresh and underground brackish water costs will be about $0.27 and $0.63 per 1,000 gallons respectively.

H. MacDougall, Technical Advisor, Resources and Transport Division, United Nations, at the International Seminar on the Economic Application of Water Desalination (Mac Dougall, 1965) stated:

> "Research now being conducted by the Robert A. Taft Sanitary Engineering Center in U.S.A. indicates that $0.54 per 1,000 gallons is required for processing a 10 million gallons per day plant."

This cost will be considered for effluent water processing in Kuwait, since no data is now available.

Conveyance Cost

Conveyance facilities begin at the supply source and extend to the end points of the distribution system. Capacity, transmission distance, and means of conveyance are the principal factors influencing costs. In a conventional water supply system, pipeline cost represents about 70 per cent of the total system's value and approximately 30 per cent of the total system is allotted for intake, storage, and treatment facilities (Koenig, 1959). Approximately 87 per cent of the pipeline value is allotted for 6 per cent interest and an estimated equipment depreciation of 50 years. Approximately 6 per cent of the remaining 13 per cent of the pipeline investment value is allotted for energy and about 7 per cent for operation, maintenance, and repair costs (United Nations, 1965). These percentages would, of course, vary in different places due to physical characteristic differences, varyance in the economic systems, and other factors. However, it indicates the order of magnitude which can be adjusted to differences in pipe cost, materials, labor, interest rates, and other conditions.

An efficient water distribution system must be developed in Kuwait. The system's cost will depend upon such factors as conveyance technique, supply and production capacities, transmission distances, unit energy production costs, hydraulic pipeline gradients, and roughness coefficients. F. P. Linaweaver (Linaweaver, 1964) stated:

> "With the exception of the work done by Koenig, no report that evaluated the effect of even a majority of these parameters was found in the literature."

Conveyance, capital, maintenance, and operation costs for water resource development generally are defined in the following paragraphs.

Capital Costs

Capital costs are correlated between design capacities and costs per mile. A regression analysis was established (Linaweaver Jr., 1964) between pipeline costs for a variable diameter, D, in inches, and capital cost, K, in dollars per mile. The formula is

$$K = 1{,}890\ D^{1.29}$$

with a correlation factor of 0.98. To convert dollars per mile for the capital cost to dollars per thousand gallons per mile for unit cost, the uniform annual cost of capital recovery must be a function of the annual volume of water transported. The unit capital cost becomes:

$$C_K = \frac{Kf}{365 \times 1 \times Q \times 0.75 \times 10^3}$$

in which C_K is the unit capital cost in dollars per thousand gallons per mile; K is capital cost in dollars per mile; f is the capital recovery factor,

$$f = \frac{i\ (1 + i)^n}{(1 + i)^n - 1};\ 635 \times 10^3 \times Q$$

in thousands of gallons per year with capacity Q factored into millions of gallons per day; 0.75 is the load building factor (Linaweaver, 1964).

Operation and Maintenance Costs

Operation and maintenance costs basically are pumping energy costs, and operation and maintenance expenses. The unit energy cost is,

$$C_e = \frac{(\sum S)P}{E} \quad (1.66 \times 10^{-2})$$

in which C_e is unit energy cost in dollars per thousand gallons per mile, $\sum S$ is the sum of specific energy requirements in foot-pounds per thousand feet, P is the energy cost in dollars per kilowatt hour, E is the efficiency factor, and the value 1.66×10^{-2} is a conversion factor. Specific energy requirements include a friction loss, S_f, and an average line slope S_L. Both S_L and S_f are multiplied by a load factor. For S_L the 0.75 load building factor is equivalent to pumping an average of 750 gallons for each 1,000 gallons of design capacity. Because S_L will be constant throughout the load building term, the load building factor for S will be 0.75. In the Hazen-Williams equation, S_f varies approximately as Q^2 . The load building factor is equivalent to pumping one-third of the design flow, since S_f is proportional to Q^2 and the average altitude of the resulting parabola (S_f plotted against Q) is one-third. During the second 50 years the full design flow is pumped. The equivalent flow being pumped during the entire 100 years is therefore the average of one-third of the maximum efficiency and equals one to two-thirds. Therefore,

$$C_e = \frac{(0.75\ S_1 + 0.667\ S_f)P}{E} \times 1.66 \times 10^{-2}$$

in which S_f is obtained from the Hazen-Williams expression as,

$$S_f = \frac{10^3 \times Q^{1.85}}{405 \times 10^{-6} \times CXD^{2.63}}$$

in which S_f is feet per thousnad feet, C is the Hazen-Williams coefficient, and D is the diameter in inches.

The total unit transmission cost, C_t , in dollars per thousand gallons per mile is:

$$C_t = C_k + 1.08\ C_e$$

allowing 8 per cent of the energy cost for other operation and maintenance expenses (Koenig, 1959).

The previous figure by Koenig established a relationship between capacity and cost for distances from 25 to 300 miles by tank trucks and pipeline conveyance as shown in Figure 4-3. From the figure it may be seen that for short distances and in limited quantities, tank truck water conveyance is economical.

The following table is reproduced from Koenig's background paper and submitted by the United Nation Secretariat (United Nations, 1965) to illustrate hydraulic gradient effects on pipeline conveyance costs.

Gradient ft/mile	50	20	5*	0	-20	-50
Average Convey-ance Rate m.g.p.d.						
.01	0.291	0.242	0.217	0.209	0.180	0.162
.1	0.046	0.039	0.0354	0.0342	0.030	0.026
1	0.014	0.011	0.0088	0.0082	0.0071	0.0059
10	0.0078	0.0051	0.0037	0.00325	0.0023	0.0018
100	0.0057	0.0030	0.0017	0.0013	0.00064	0.00059
1000	0.0048	0.0022	0.0009	0.00051	0.00024	0.00019

*This column has been added by the author to suit the required slope.

Conveyance Cost for Kuwait

The hydraulic gradient of land in Kuwait will be considered an average of five feet per mile; the average conveyance rate is shown in the following curve (Figure 5-1) in which processing cost prices for 5, 33, 60, and 100 m.g.d. are 4.5×10^{-3}, 2.5×10^{-3}, 2×10^{-3} and 1.7×10^{-3} dollars per 1,000 gallons/mile respectively. The average conveyance distance is considered to be 40 miles. The capacity for each water resource and conveyance cost price is, therefore, determined.

Mathematical Model for Kuwait

A mathematical model will now be presented with its physical constraints, followed by a representation table for its maximum production quantities, and finally a

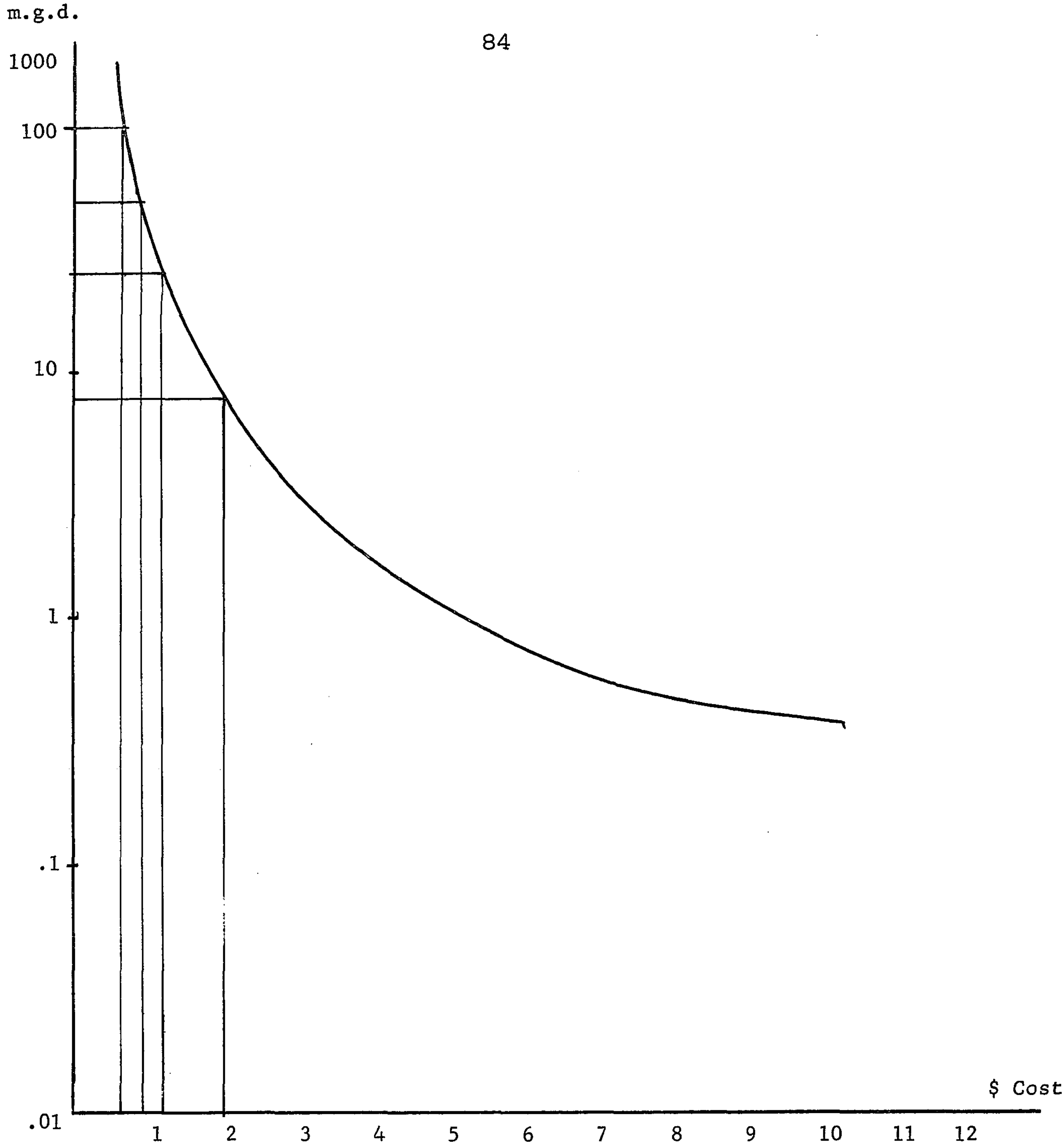

Figure 5-1

Cost of gradient and plant production

mathematical equation identifing the unit cost and its relation to the conveyance cost, unit cost production, and the required quantities to satisfy the needs with the minimum cost.

The constraints are as follows:

1. Distilled sea water (X_1) will be $42 \leq X_1 \leq 60$ m.g.d.

2. Underground fresh water (X_2) will be $0 \leq X_2 \leq 5$ m.g.d.

3. Underground brackish water (X_3) will be $75 \leq X_3 \leq 100$ m.g.d.

4. Effluent water (X_4) will be $15 \leq X_4 \leq 33$ m.g.d.

and the constraint relationship will be as follows:

1. $X_1 + X_2 + X_3 + X_4 \geq 150$ m.g.d., total

2. $1.07\ X_1 + X_2 \leq 60$ m.g.d.

   domestic

3. $1.07\ X_1 + .10\ X_3 \geq 45$ m.g.d.

4. $.9\ X_3 + .02\ X_1 + X_4 \leq 100$ m.g.d.

   non-domestic

5. $.9\ X_3 - .07\ X_1 + X_4 \geq 75$ m.g.d.

which is to say that:

1. Total quantity needed is 150 m.g.d. for the whole country.

2. Seven per cent from the brackish water is used to make distilled water more palatable, ane none, some and/or all of the underground fresh water is used.

3. Required quantities are taken from distilled water,

underground fresh water is kept in reserve, and 10 per cent from the underground brackish water for domestic uses other than drinking.

4. 90 per cent underground brackish and all available effluent water is used, plus two per cent distilled water for agricultural and industrial purposes.

5. 90 per cent of the available underground brackish water and all the effluent is used for agricultural and industrial purposes, minus 7 per cent of the distilled water.

The optimum solution, will be represented in the form of the minimum quantity with the maximum efficiency, the following table identifies the maximum capacity of each source of water and its conveyance cost.

Source	Symbol	Max. Cap. m.g.d.	Prod. Cost t/g	Conveyance	Total Cost t/g	Remarks
Distilled	X_1	60	$1.09	$.08	$1.17	Based on
Fresh	X_2	5	$ .63	$.18	$0.81	distance
Brackish	X_3	100	$ .27	$.07	$0.34	of 40
Effluent	X_4	33	$ .54	$.10	$0.64	miles

The primary goal is to minimize the unit cost price y which is equal to

$$Y = 1.17\,X_1 + .81X_2 + .34X_3 + .64X_4$$

From the previous equations and constraints an optimum solution for water resources in Kuwait can now be obtained.

Through linear programming (IBM, 1968) the optimum solution is found as

$$X_1 = 42 \text{ m.g.d.}$$

$$X_2 = 0$$

$$X_3 = 93 \text{ m.g.d.}$$

$$X_4 = 15 \text{ m.g.d.}$$

which indicates that 60 per cent of the water needs should be taken from brackish resources, about 30 per cent by distillation, and 10 per cent from effluent, leaving the fresh ground water as a reserve in times of emergency.

Extension of the Basic Model

The above model can be generalized and adjusted as local constraints demand and advancement in technology exist, viz. In the State of Kuwait it is possible to extend the capacity of the model to contain additional sources with other assumptions introduced in its manipulations. As an example, the following constraints will be considered in building a second model.

1. Distilled sea water (X_1) will be $0 \leq X_1 \leq 5$ m.g.d.
2. Underground brackish water (X_2) will be $0 \leq X_2 \leq 5$ m.g.d.
3. Underground brackish water (X_3) will be $0 \leq X_3 \leq 33$ m.g.d.

4. Effluent water (X_4) will be $15 \leq X_4 \leq 33$ m.g.d.

5. Fully treated (distilled) underground brackish water (X_6) will be $42 \leq X_6 \leq 60$ m.g.d.

6. Partially treated sea water (X_5) will be $0 \leq X_5 \leq 15$ m.g.d.

and the constraints relationship will be

1. $X_1 + X_2 + X_3 + X_4 + X_5 + X_6 \geq 150$ m.g.d.

2. $1.07\ X_5 + X_2 \geq 60$ m.g.d.

3. $1.07\ X_5 + .10X_3 \leq 45$ m.g.d.

4. $.44X_3 + X_4 + X_6 \leq 100$ m.g.d.

5. $.44X_3 + X_4 + X_5 + X_1 \geq 75$ m.g.d.

6. $X_1 + X_6 \geq 20$

The characteristic of the above model is determined on the following criteria.

1. Total quantity needed is 150 m.g.d. for the domestic and non-domestic uses.

2. Seven per cent of the distilled water is taken from the brackish water to make the distilled water more palatable, and none, some and/or all of the underground fresh water is used.

3. Required quantities of water are taken from the fully treated underground brackish water for domestic uses and ten per cent of the brackish water for non

domestic uses.

4. 44 per cent of the underground brackish water plus all available effluent water and the quantity needed from partially treated water.

5. 44 per cent of the underground brackish water plus all available effluent water, plus fully treated sea water and distilled water from the underground brackish water if needed to satisfy the agricultural and industrial uses.

The optimum solution will be represented in the form of the minimum quantity with the maximum capacity of each source of water and its conveyance cost.

Source	Symbol	Max. Cap. m.g.d.	Prod. Cost t/g	Conveyance	Total Cost t/g	Remarks
Distilled	X_1	5	$1.09	$.08	$1.17	Based on
Fresh	X_2	5	$ .63	$.18	$ .81	distance
Brackish	X_3	33	$ .27	$.07	$ .34	of 40
Effluent	X_4	33	$ .54	$.10	$ .64	miles
Brackish from sea	X_5	60	$ .47	$.08	$ .55	
Distilled from sea	X_6	15	$ .95	$.27	$1.22	

The primary goal is to minimize the unit cost y which is equal to (IBM, 1968)

$$y = 1.17X_1 + .81X_2 + .34X_3 + .64X_4 + .55X_5 + 1.22X_6$$

As with the first model, an optimum solution can be obtained using the available linear programming techniques

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

The presence of water has been essential for the development of life on earth. Even ecologically adapted desert plants and animals are absolutely dependent upon a minimal supply of water for their existence. However, in contrast to the surface water generally availabel in temperate climates, desert water sources usually are underground or in rivers which originate in temperate regions.

The earth's total land surface has been estimated at about 25 x 10^9 acres. About 7.04 x 10^9 acres (28 per cent) are under cultivation. Most of the remainder, about 18 x 10^9 acres (72 per cent) is classed either as arid or semi-arid and generally unsuited to cultivation and human life (White, 1956).

Man's ability to exploit his environment has always been determined by his control of useable water. His needs have been greatest and his abilities have been weakest in desert areas. Despite his intellectual, economic and political progress, man still has not pernamently solved the problem of obtaining sufficient, continuous water supplies in desert areas. Rather, his problems have intensified through population growth and general improvement of his standard of living. In addition, the problem has become crucial to oil and mining industries as they expand into desert regions.

This dissertation discussed some possible solutions to the water resources problem in desert areas. An example of the practical application of the basic principles proposed has been given for the state of Kuwait.

Arid region water sources which were considered included: distilled water, underground brackish water, underground fresh water, and effluent water, all or some of which exist or potentially exist in the desert lands.

Conversion of salt or brackish water into useable fresh water will be considered as a major potential water supply for domestic use in arid areas, particularly in areas where no surface water exists. Unfortunately, comprehensive statistical data are needed for appraisal of the economic feasibility of partial or total use of desalted water for various needs. This data is difficult to obtain because of its potential for rapid change, i.e., the permissible cost of separating fresh water from saline supplies depends upon the urgency of the existing needs (irrigation, industrial or domestic).

In addition, local conditions govern the possibility of blending distilled and saline sources to produce an economical and acceptable potable water supply. As a rule, fresh water scarcity will promote greater tolerance of lower water quality for many uses.

In desert areas sustained oil and mining production cannot be maintained and successfully developed unless permament commercially successful agriculture can be achieved. Water quality requirements for cultivation vary widely, and include the total percentage of dissolved salts. Also, soil types and conditions, and suitable crop selection are variables of great importance.

To formulate the problem in a mathematical model it should be presented in its principal components. The maximum effect of each of these components will be grouped and analyzed to determine the demands or variability of each group.

It is suggested that the data be analyzed (or presented) in the following manner:

I. System parameters

A. Water supplies (actual and potential)

1. Distilled sea water
2. Underground fresh
3. Underground brackish
4. Effluent
5. Treated brackish

B. Water demands

1. Municipal
2. Agricultural
3. Industrial

Water supply limits and water demand potentials must be identified. The unit cost, Y, will represent actual water (retrieval) and conveyance costs in the formula,

$Y = (C_{11}+C_{12})X_1 + (C_{21}+C_{22})X_2 + (C_{31}+C_{32})X_3 + (C_{41}+C_{42})X_4$

in which C_{11}, C_{21}, C_{31}, and C_{41} represent retrieval costs for distilled, underground fresh, underground brackish and effluent water respectively, and C_{12}, C_{22}, C_{32}, and C_{42} represent conveyance costs of each. X_1, X_2, X_3, and X_4 represent the quantity of water needed from each source for the optimal solution, i. e., minimum cost. The model developed herein can be represented by the following matrix of requirement vs. cost of the seven resource variables:

	X_1	X_2	X_3	X_4
Y_1	A_{11}	A_{12}	A_{13}	A_{14}
Y_2	A_{21}	A_{22}	A_{23}	A_{24}
Y_3	A_{31}	A_{32}	A_{33}	A_{34}
Y_4	A_{41}	A_{42}	A_{43}	A_{44}
Y_5	A_{51}	A_{52}	A_{53}	A_{54}
Y_6	A_{61}	A_{62}	A_{63}	A_{64}
Y_7	A_{71}	A_{72}	A_{73}	A_{74}

The A's represent cost dependent variables.

Optimal solution of the matrix requires objective equations based upon existing (and potential) constraints, and successful application of linear programming techniques.

In summary, this dissertation offers a unique, optimum solution for water resource development of arid areas, specifically where there is no surface water, and the rainfall is negligible. Unfortunately, space limitations and lack of sufficient reliable data impair its accurate completion here. The dissertation's strength is its unique and comprehensive structuring of the problem and its rigorous technique for defining and obtaining the optimum solution.

By applying the above technique to the state of Kuwait, it is recommended that the municipal and domestic users should have priority claims to distilled water, while brackish and effluent water should be blended for agricultural and industrial users. Underground fresh water was considered only as an emergency reserve. With these priorities established, harmonious short term and long term water resource development plans should be put into effect, beginning with a dual water distribution system to serve each set of users. To control this system, multipurpose plants should be built to produce power, steam for industrial purposes and distilled water.

For theoretical purposes, the derived mathematical model has shown to be adequate. Its application to a specific problem awaits only the collection of appropriate data.

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APPENDIX A

TABLE I

MONTHLY RAINFALL IN MILLIMETERS IN THE STATE OF KUWAIT

(Planning Board 1966)

Month	Years									
	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965
January	18.8	9.8	12.1	32.2	7.7	22.7	27.1	.4	12.2	63.5
February	4.7	14.3	.7	13.5	2.6	16.2	3.2	23.9	2.2	
March	6.0	15.4	7.6	10.0	2.7	45.9	4.5	1.4	2.2	2.8
April	4.2	26.3	2.2	4.2	29.1	18.9	19.9			8.4
May		8.9	1.9	1.8		1.1	.1	21.4		8.8
June										
July										
August										
September										
October										
November		89.1	15.7	9.3	11.3	66.3	.2	7.2	1.1	6.5
December	119.3	1.3	61.7	23.8	0.1	14.4	12.7	13.1	8.6	
Total	155.0	165.1	101.9	100.	28.6	195.7	66.7	87.3	26.3	108.7

TABLE II

POPULATION OF KUWAIT

(Planning Board 1966)

Date	Kuwaities	Non-Kuwaities	Total
February 1957	113,622	19,947	208,473
May 1961	161,909	43,466	321,621
April 1965	220,059	73,537	467,339

TABLE III

POTABLE WATER PRODUCED FOR GENERAL CONSUMPTION IN KUWAIT

(Planning Board)

	Distilled Water mg	Brackish Water mg	Sweet Water mg	Consumption Total mg
1953	116			116
54	234			234
55	345	17		362
56	494	17		521
57	631	40		671
58	300	44		944
59	1,135	64		1,199
1960	1,301	95		1,396
61	1,014	76		1,590
62	1,590	90	117	1,797
63	1,271	58	767	2,096
64	1,488	85	689	2,262
65	1,486	74	990	2,557

TABLE IV

THE FRESH WATER RESERVOIR

Locations, Number and Capacity in Kuwait

(Ministry of Guidance 1963)

District	Number Of Reservoirs	Capacity
Shuwaikh	1	3,600,000
Shuwaikh	1	3,600,000
Shuwaikh	1	12,000,000
Hawaii	1	12,000,000

TABLE V

THE FRESH WATER STORAGE TOWERS

Location, Number, and Capacity in Kuwait

(Ministry of Guidance 1963)

District	Number of Towers	Capacity (Gallons)
Sha'b Gate	1	192,000
Industrial Area	1	192,000
Kifan	1	600,000
Hawaii	1	600,000
Salmiyah	1	494,000
Farwaniah	1	300,000

TABLE VI

FRESH WATER DISTRIBUTION STATIONS

Location and Number in Kuwait

(Ministry of Guidance 1963)

Serial No.	District	Number
1	Sha'b Gate	2
2	Green Belt	1
3	Industrial Area (Harbout Dist)	1
4	Bitumen Mixing Plant	1
5	Industrial Area (Ahmedi Road)	1
6	Farwaniyah	1
7	Garden (Old Airport)	1
8	Research	1
9	South Shuwaikh	1
10	Salmiyah	1
11	Education Garage	1
12	Housing Station	1
13	Jahra Station	1
	Total	14

TABLE VII

BRACKISH WATER SUPPLIED FOR IRRIGATION AND OTHER USES

Non Potable Water (Ministry of Guidance 1963)

Year	Total Produced (Gallons)	Average Daily Production
1954	187,923	514
1955	252,723	692
1956	376,814	1,032
1957	522,832	1,475
1958	817,643	2,240
1959	1,185,195	3,247
1960	1,529,025	4,189
1961	1,886,034	5,167
1962	2,968,941	8,134
1963	3,342,166	9,156
1964	3,116,506	9,908
1965	2,284,103	11,737

TABLE VIII

BRACKISH WATER RESERVOIRS

Location, Numbers and Capacity in Kuwait

(Ministry of Guidance 1963)

District	Number	Capacity (gallons)
Shuwaikh	1	3,000,000
Shuwaikh	1	5,000,000
Hawaii	1	5,000,000
Sulaibiyah	1	3,000,000
Total	4	16,000,000

TABLE IX

BRACKISH WATER STORAGE TOWERS

Location, Numbers, and Capacity in Kuwait

(Ministry of Guidance 1963)

District	Number	Capacity (gallons)
Sha'b Gate	1	192,000
Industrial Area	1	192,000
Kaifan	1	600,000
Hawaii	1	600,000
Salmiyah	1	499,200
Farwaniyah	1	249,600
Total	6	2,332,800

TABLE X

BRACKISH WATER DISTRIBUTION STATIONS

Location and Number in Kuwait

(Ministry of Guidance 1963)

Serial No.	Area	Number
1	Green Belt	1
2	Bitumen Mixing Plant	1
3	Industrial Area (Ahmadi Road)	1
4	Farawaniyah	1
5	Garden (Old Airport)	1
6	Research	1
7	Salmiyah	1
	Total	7

TABLE XI

UNDERGROUND FRESH WATER CONSUMPTION IN KUWAIT

(Talat 1967)

Year	Average Consumption (Gallons per day)
1962 Winter	200,000
1963 Summer	300,000
1963 Winter	200,000
1964 Summer	2,200,000
1964 Winter	1,800,000
1965 Summer	3,200,000
1965 Winter	2,600,000
1966 Summer	2,800,000
1966 Winter	2,700,000
1967 Summer	3,300,000

POPULATION ESTIMATES FOR STATE OF KUWAIT

USING DIFFERENT GROWTH RATES

	1965	1970	1975	1980	1985	1990	1995	2000
Kuwaiti (Growth @ 3%/yr)	220,000	255,000	296,000	343,000	398,000	461,000	535,000	620,000
Non-Kuwaiti (Growth @2%/yr)	248,000	274,000	303,000	335,000	370,000	409,000	451,000	499,000
Total	468,000	529,000	599,000	678,000	768,000	870,000	986,000	1,119,000
Kuwaiti (Growth @ 3½%/yr)	220,000	261,000	310,000	368,000	437,000	520,000	618,000	735,000
Non-Kuwaiti (Growth @ 2½%/yr)	248,000	281,000	318,000	360,000	408,000	462,000	522,000	590,000
Total	468,000	542,000	628,000	728,000	845,000	982,000	1,140,000	1,325,000
Average Population Estimate:	468,000	535,000	613,500	703,000	806,500	926,000	1,063,000	1,222,000

TABLE XIII

PRESENT POPULATION, DISTRICTS AND FUTURE EXPANSION FOR THE STATE OF KUWAIT

No.	District	Population	Remarks
1	Kuwait Town	100,000	
2	Bnade El-Kar	8,000	
3	Al-Dasmah	15,000	
4	Al-Mansouria	10,000	
5	Abdoulla as Salem	22,000	
6	Al Shamia	10,000	
7	Al Shuwaikh	8,000	
8	Kaifan	20,000	
9	Al Fayha	12,000	
10	Al Nozha	12,000	
11	Al Qadisiya	12,000	
12	Al Diya	10,000	
13	Al Sheb	7,000	
14	Hawalli	75,000	
15	Al-I'Dailya	15,000	
16	Al-Khalidya	8,000	
17	Al Mina (Indus)	5,000	
18	Al Sulabikat (Pub.Serv)	7,500	
19	Sulabikat Village	20,000	
20	Al Salimiyeh	50,000	
21	Al Gabriyeh	50,000	
22	A Residence	8,000	Future Expansion
23	B Residence	8,000	Future Expansion
24	C Residence	8,000	Future Expansion
25	D (Industrial)	5,000	Future Expansion
26	E (Industrial)	5,000	Future Expansion
27	Al-Rumaythiya	45,000	
28	F Residence	100,000	Future Expansion
29	G Residence	100,000	Future Expansion
30	H Residence	100,000	Future Expansion
31	I Residence	50,000	Future Expansion
32	J Residence	50,000	Future Expansion
33	K (Industrial)		Future Expansion
34	Al Gahra Village	150,000	
35	Jleeb Al-Shuyuk	22,000	
36	Al-Fintas	30,000	

TABLE XIII (Continued)

37	Abu Haliefah	20,000
38	Al-Mangaf	4,000
39	Al-Fahahil	45,000
40	Al-Shuaibeh (Industrial)	60,000

TABLE XIV

Water Consumption

I. Distilled Water

Supply "A" = 60 m.g.p.d.

No.	District	Water Consumption m.g.d.
1	Kuwait Town	5.000
2	Bnade El-Kar	0.400
3	Al-Dasmah	0.750
4	Al-Mansouria	0.500
5	Abdoulla as Salem	1.100
6	Al Shamia	0.500
7	Al Shuwaikh	0.400
8	Kaifan	1.000
9	Al Fayha	0.600
10	Al Nozha	0.600
11	Al Qadisiya	0.600
12	Al Diya	0.500
13	Al Sheb	0.350
14	Hawalli	3.750
15	Al I'Dailya	1.500
16	Al-Khalidya	0.400
17	Al Mina (Indus)	0.500
18	Al-Sulabikat	0.750
19	Sulabikat Village	1.000
20	Al Salimiyeh	2.500
21	Al Gabriyeh	2.500
22	A Res	0.400
23	B Res	0.400
24	C Res	0.400
25	D (IND)	0.500
26	E (IND)	0.500
32	J Res	2.500
33	K (IND)	0.550
35	Jleeb Al-Shuyuk	1.100

TABLE XV

WATER CONSUMPTION

I. Distilled Water

Supply "B"

No.	District	Water Consumption m.g.d.
27	Al-Rumaythiya	2.200
28	F Res	5.000
29	G Res	5.000
30	H Res	5.000
31	I Res	2.000
36	Al-Fintas	1.500
37	Abu Haliefah	1.000
38	Al-Mangaf	1.000
39	Al-Fahahil	2.000
40	Al-Shuaibeh (IND)	3.000

TABLE XVI

WATER CONSUMPTION

II. Brackish Water

Supply A = 20 m.g.p.d.

No.	District	Water Consumption
1	Kuwait Town	.200
2	Bnade El-Kar	.375
3	Al-Dasmah	.250
4	Al-Mansouria	.550
5	Abdoulla as Salem	.250
6	Al Shamia	2.500
7	Al Shuwaikh	.200
8	Kaifan	.500
9	Al Fayha	.300
10	Al Nozha	.300
11	Al Qadisiya	.250
12	Al Diya	.300
17	Al Mina (Indus)	7.125
25	D (IND)	3.875
32	J Res	3.025

TABLE XVII

WATER CONSUMPTION

II. Brackish Water

Supply B = 20 m.g.p.d.

No.	District	Water Consumption
18	Al-Sulabikat	5.000
19	Sulabikat Village	5.000
26	E (IND)	5.000
33	K (IND)	5.000

TABLE XVIII

WATER CONSUMPTION

II. Brackish Water

Supply C = 12 m.g.p.d.

No.	District	Water Consumption
13	Al Sheb	.400
14	Hawalli	1.800
15	Al-I'Dailya	1.000
16	Al-Khalidya	.200
20	Al Salimiyeh	1.000
21	Al Gabriyeh	1.000
22	A Res	.200
23	B Res	.200
24	C Res	.200
29	G Res	2.500
30	H Res	2.500
31	I Res	1.000

TABLE XIX

WATER CONSUMPTION

II. Brackish Water

Supply D = 48 m.g.p.d.

No.	District	Water Consumption
27	Al-Rumaythiya	1.125
28	F Res	2.500
35	Jleeb Al-Shuyuk	.550
36	Al-Fintas	4.825
37	Abu Haliefah	6.000
38	Al-Mangaf	9.000
39	Al-Fahahil	10.000
40	Al-Shuaibeh (IND)	14.000

APPENDIX B

TABLE XX

NETWORK DESIGN

Supply A-D

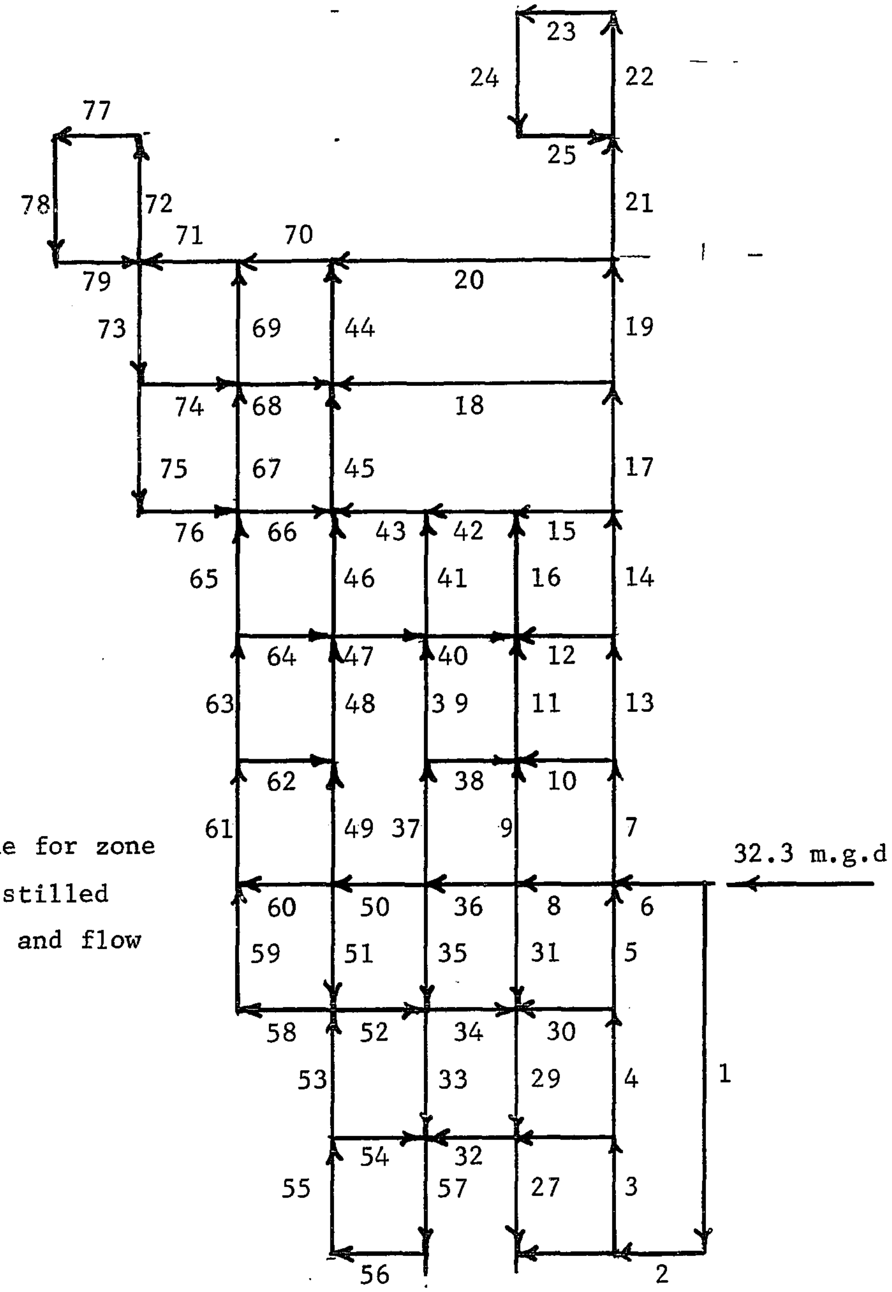
Pipe No	Mgd	D Inches	Gpm	C	V ft/sec	L feet
1	9.55	30	6631.9	140	3.15	25591.8
2	6.55	24	4548.6	140	3.20	8530.60
3	5.55	24	3854.2	130	2.71	2624.80
4	5.15	24	3576.4	130	2.71	6520
5	3.9	20	2708.3	140	2.84	1968.60
6	20	42	13888.9	140	3.22	11811.60
7	3.9	20	2708	140	2.84	3937.60
8	20	42	13888.9	140	3.22	3781.00
9	2	14	1388.9	140	2.9	8530.60
10	.5	8	347.2	130	2.22	4593.4
11	2	14	1388.9	130	2.22	3937.20
12	.5	8	347.2	130	2.22	3937.20
13	2.8	16	1944.4	140	3.10	3937.20
14	2.3	14	1597.2	140	3.48	6520
15	.2	6	138.9	100	1.58	5249.60
16	2	14	1388.9	140	2.9	6520
17	1.9	14	1319.4	140	2.75	7874.40
18	.5	8	347.2	130	2.44	14436.40
19	1.4	12	972.2	140	2.76	17061.20
20	.4	8	277.8	100	1.77	11811.60
21	1.00	12	694.4	140	1.97	9186.80
22	1.00	12	694.4	140	1.97	9186.80
23	.75	10	520.8	130	2.13	2624.8
24	.50	8	347.2	130	2.22	9186.80
25	.25	6	173.6	100	2.05	2624.8
26	1.00	12	694.4	140	1.97	9186.80
27	1.00	12	694.4	140	1.97	2624.80
28	.2	6	138.9	100	1.58	5249.6
29	.8	10	555.6	130	2.27	9186.80
30	.25	6	173.6	100	2.05	3937.20
31	.55	8	381.9	130	2.44	3937.20
32	1.3	10	902.8	140	3.69	3937.20
33	4.4	20	3055.6	140	3.19	3937.20
34	.25	6	173.60	100	2.44	5249.6

TABLE XX (Continued)

Pipe No	Mgd	D Inches	Gpm	C	V ft/sec	L feet
35	5.00	20	3472.2	140	3.55	4593.40
36	17.45	36	12118.05	140	3.94	4593.40
37	4	18	2777.8	140	2.96	3937.20
38	.3	6	208.3	130	2.36	3937.20
39	3.4	18	2361.1	140	3.07	5249.6
40	.3	6	208.3	130	2.36	4593.40
41	2.8	16	1944.4	140	3.10	7218.20
42	2	14	1388.9	140	2.9	4593.40
43	3.8	18	2638.9	140	3.5	4593.40
44	4.6	20	3194.4	140	3.55	6520
45	4.6	20	3194.4	140	3.55	6520
46	1.2	10	833.3	140	3.4	4593.4
47	.5	8	347.2	130	2.2	5249.6
48	2.7	16	1875	140	3.10	5905.80
49	2.7	16	1875	140	3.10	6520
50	8.45	16	5868	140	2.68	7874.40
51	3.750	18	1909.7	140	3.5	9186.80
52	.27	6	187.5	130	2.36	11811.60
53	2.6	16	1805.6	140	3.10	3281
54	.35	6	243.0	130	2.36	5905.80
55	2.95	16	2048.6	140	3.10	13124
56	5.45	20	3784.7	140	3.90	11811
57	5.45	20	3784.7	140	3.90	20998.40
58	1.6	12	1180.6	140	3.15	5420
59	.6	8	416.7	130	2.66	10499
60	22	14	1380.9	140	2.9	7218.20
61	2.1	14	1458.3	140	3.18	7874.40
62	.2	6	138.9	100	1.58	5249.60
63	1.7	12	1180.6	140	3.35	5249.60
64	.2	6	138.9	100	1.58	5249.60
65	1.3	10	902.8	140	3.69	5249.60
66	.2	6	138.9	100	1.58	5249.60
67	.9	10	625	130	2.55	5249.60
68	.5	8	347.2	130	2.20	5249.60
69	.20	6	138.9	100	1.58	5249.60
70	4.15	20	2951.4	140	3.19	5249.60
71	4.25	20	2881.9	140	3.19	13124
72	1.1	18	763.9	140	3.07	10499
73	3.05	8	2118.0	130	2.44	13780.20
74	.55	8	318.9	130	2.44	15748.80

TABLE XX (Continued)

Pipe No	Mgd	D Inches	Gpm	C	V ft/sec	L feet
75	2	14	1388.9	140	2.9	5249.60
76	1.00	12	694.4	140	1.97	14436.40
77	.8	8	555.6	130	3.55	3937.20
78	.55	8	381.9	130	2.44	15278.80
79	.25	6	173.6	100	2.05	6562



Network plane for zone
A - Distilled
pipe numbers and flow
direction

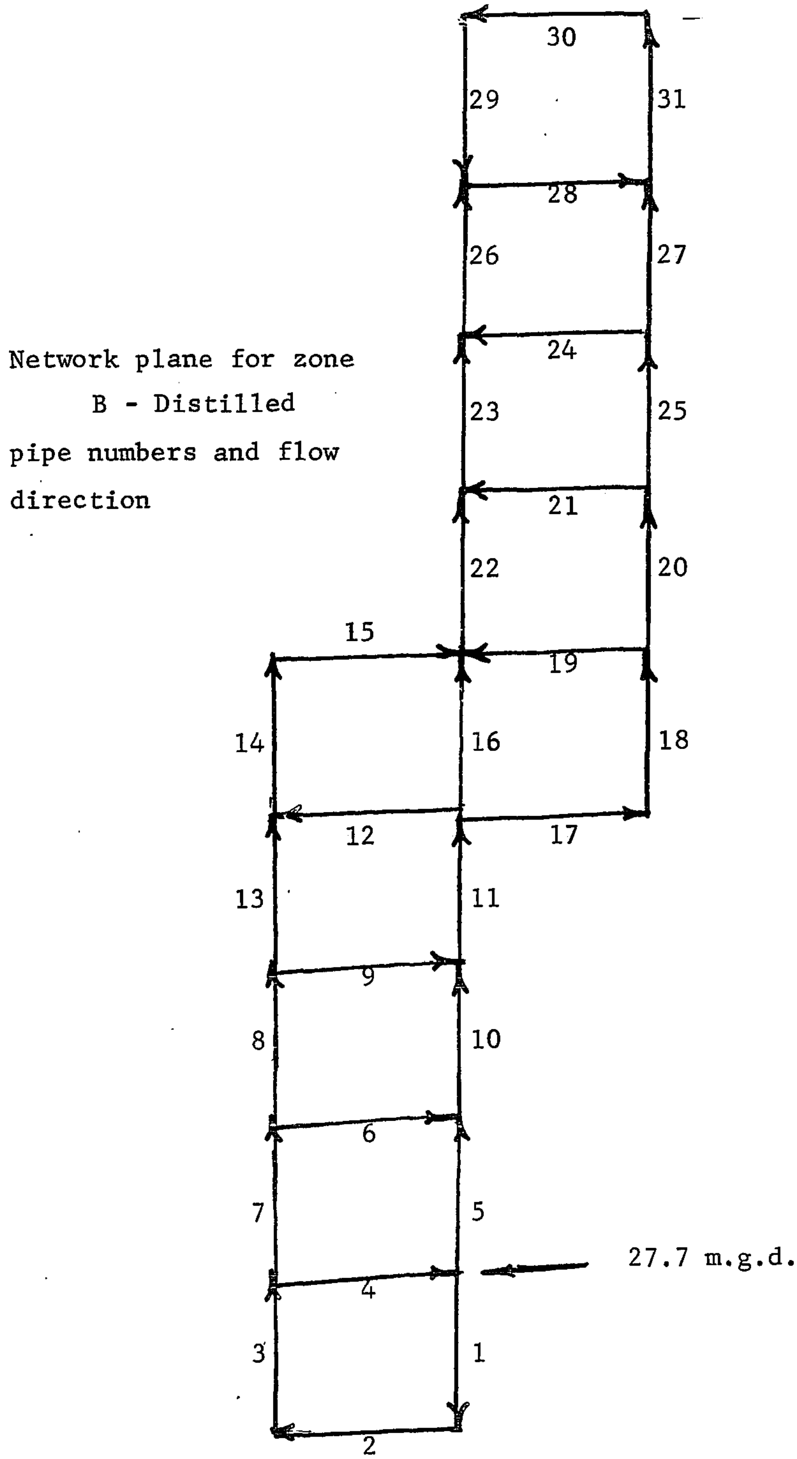
Figure 1

TABLE XXI

NETWORK DESIGN

Supply B-D

Pipe No	Mgd	D Inches	Gpm	C	V ft/sec	L feet
1	10	30	6944.4	140	3.15	7874.4
2	9	30	6520	140	2.84	6562
3	8	30	5555.6	140	2.68	21654.6
4	1	12	694.4	140	1.97	11155.4
5	17.7	36	12291.7	140	3.94	15748.8
6	..5	8	347.2	130	2.2	7874.4
7	6	24	4166.7	140	2.96	5249.6
8	4.5	20	3125.0	140	3.19	11811.60
9	.5	8	347.2	130	2.20	15748.8
10	17.7	36	12291.7	140	3.94	7874.4
11	17.7	36	12291.7	140	3.94	14436.4
12	1	12	694.4	140	1.97	13124
13	4	18	2777.8	140	2.96	14436.4
14	4	18	2777.8	140	2.96	15748.8
15	3.5	16	2430.6	140	3.87	13124
16	.5	8	347.6	130	2.2	13124
17	16.2	36	11250	140	3.72	23623.20
18	15.2	36	10655.6	140	3.50	14436.4
19	1.2	10	833.3	140	3.4	23623.20
20	1.2	10	833.3	140	3.4	10499.20
21	3	16	2083.3	140	3.32	13124
22	3	16	2083.3	140	3.32	13124
23	3	16	2083.3	140	3.32	9186.8
24	3	16	2083.3	140	3.32	15748.8
25	7	24	4861	140	3.45	6562
26	1.5	12	1041.7	140	3.15	7874.4
27	2	14	1388.9	140	2.9	5249.6
28	1.5	12	1041.7	140	3.15	15748.8
29	1.00	12	694.4	140	1.97	5249.6
30	1.5	12	1041.7	140	3.15	13124
31	2	14	1388.9	140	2.9	5249.6


Network plane for zone
B - Distilled
pipe numbers and flow
direction
30
29
31
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7
5
27.7 m.g.d.
4
3
1
2

Figure 2

TABLE XXII

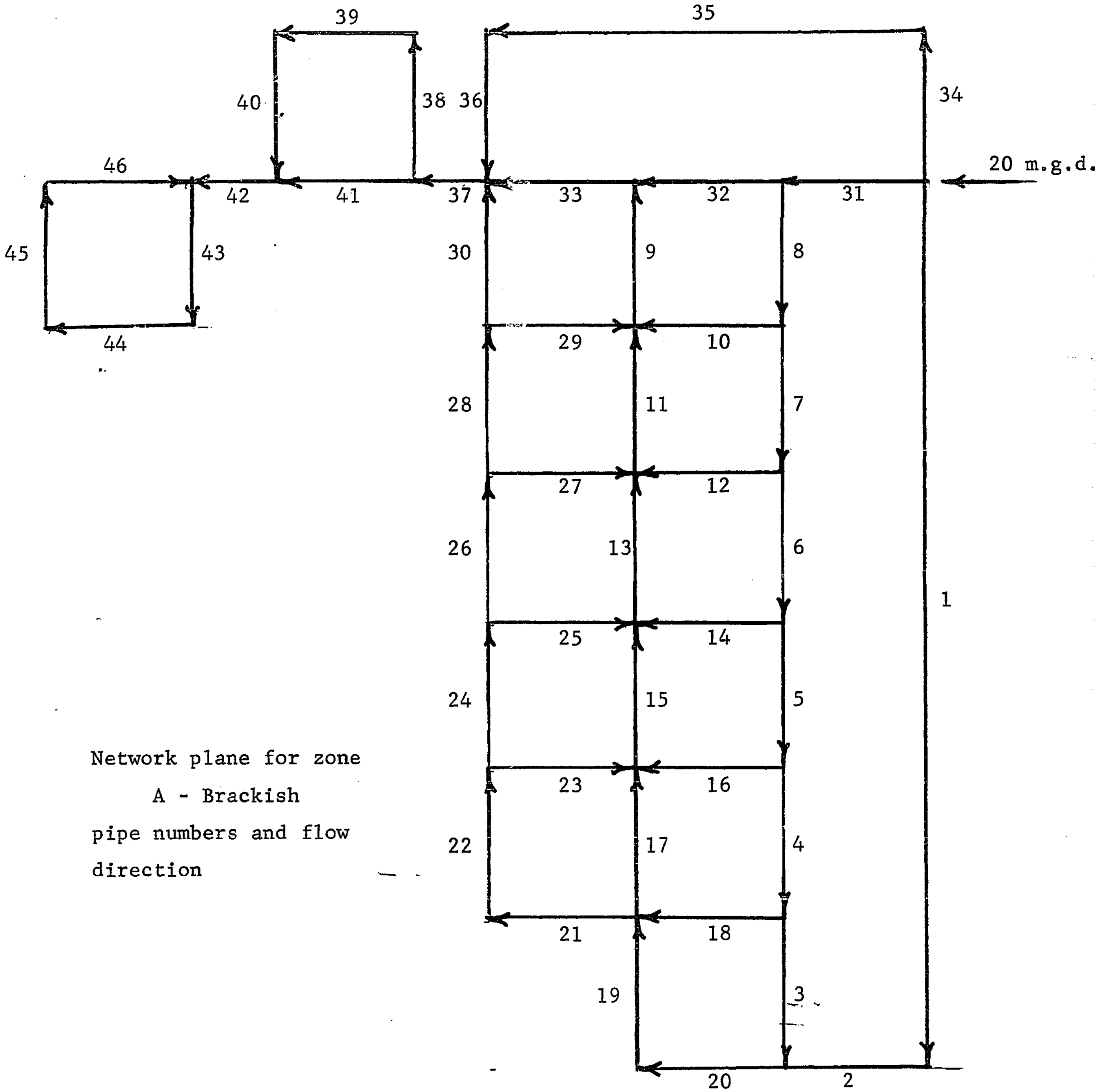
NETWORK DESIGN

Supply A-B

Pipe No	Mgd	D Inches	Gpm	C	V ft/sec	L feet
1	6.5	24	4513.9	140	3.2	25591.80
2	5	20	3472.2	140	3.55	85360.60
3	.10	4	69.4	130	1.78	2624.80
4	.3875	8	269.2	130	1.77	6562
5	.5125	8	355.90	130	2.44	1968.5
6	.7875	10	546.9	130	2.27	3937.2
7	.9125	10	633.7	130	2.84	3937.2
8	1.1125	10	772.56	130	3.40	6562
9	.6375	8	442.7	140	2.88	6562
10	.20	6	138.9	100	1.58	3937.2
11	.7625	8	529.5	130	3.55	5905.8
12	.125	6	86.8	100	1.10	4593.4
13	1.0375	10	720.5	140	3.12	4593.4
14	.275	6	190.97	100	2.21	3281
15	1.1625	10	807.3	140	3.40	3937.2
16	.125	6	86.8	100	1.58	3937.2
17	1.35	10	937.50	130	3.97	9185.8
18	.1875	6	130.20	100	1.58	5249.60
19	4	18	2777.8	140	3.5	2624.8
20	4	18	2777.8	140	3.5	9185.8
21	2.650	16	1840.3	140	3.10	3937.2
22	2.650	16	1840.3	140	3.10	3937.2
23	.125	6	86.8	100	1.58	5249.6
24	2.4	14	1666.7	140	3.48	4593.4
25	.150	4	104.2	100	2.84	4593.4
26	2.1	14	1458.3	140	3.18	3937.2
27	.150	4	104.2	100	2.84	3937.2
28	1.8	14	1250.0	140	2.60	5249.6
29	.150	4	104.2	100	2.84	4593.4
30	1.50	12	1041.7	140	2.96	7218.2
31	4.375	20	3038.2	140	3.19	8530.60
32	3.2625	16	2265.6	140	3.87	5249.6
33	3.9	20	2708.3	140	2.84	4593.4
34	9.125	30	6336.8	140	3.14	7874.4
35	7	24	4861.1	140	3.45	14436.4
36	4	18	2777.8	140	3.50	6562

TABLE XXII (Continued)

Pipe No	Mgd	D Inches	Gpm	C	V ft/sec	L feet
37	6.9	24	4791.66	140	3.45	5249.60
38	3.875	18	2691.7	140	3.50	13780.20
39	2.875	16	1996.5	140	3.52	3937.20
40	1.00	12	694.4	140	1.97	15748.8
41	2.025	14	1406.25	140	3.18	6562
42	3.025	16	2100.7	140	3.87	5249.6
43	2.025	14	1406.25	140	3.18	5249.6
44	1.525	12	1059	140	3.15	14436.4
45	1.025	12	711.8	140	2.17	5249.6
46	.525	8	364.6	130	2.22	15748.8



Network plane for zone A - Brackish pipe numbers and flow direction

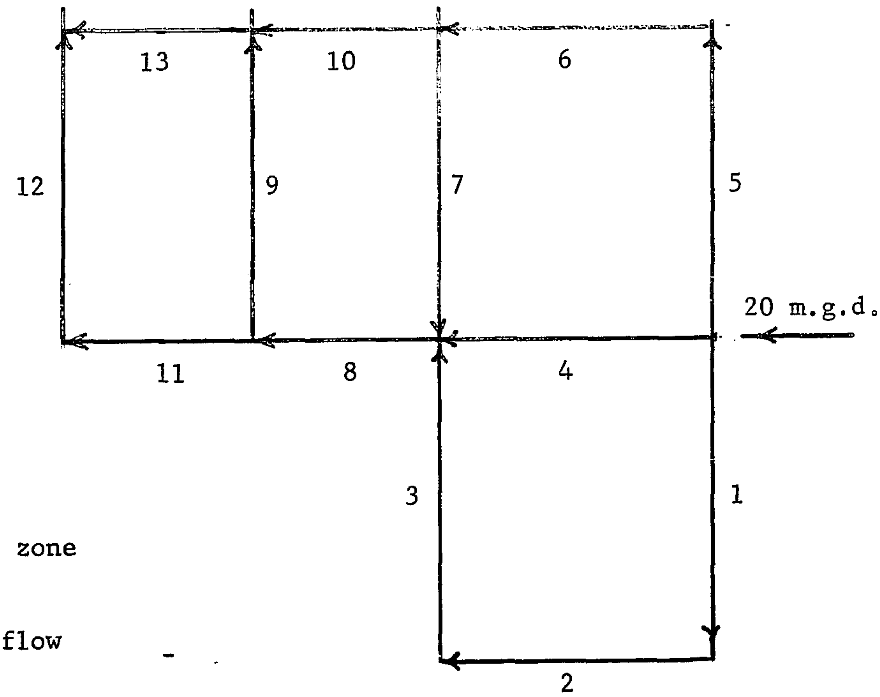
Figure 3

TABLE XXIII

NETWORK DESIGN

Supply B-B

Pipe No	Mgd	D Inches	Gpm	C	V ft/sec	L feet
1	4	18	2777.8	140	3.5	18373.6
2	2.5	14	1736.1	140	3.76	3281
3	1.5	12	1041.7	140	3.15	18373.6
4	7	24	4861.1	140	3.45	7611.92
5	7	24	4861.1	140	3.45	26248
6	5.5	24	3819.4	140	2.96	3937.2
7	1.5	12	1041.7	140	3.15	28216.6
8	4.5	20	3125.0	20	3.19	14436.4
9	1.5	12	1041.7	140	3.15	20342.2
10	2	14	1388.9	140	2.9	9843.0
11	.3	6	2083.3	130	2.36	15092.60
12	1.00	10	694.4	140	2.84	3281.00
13	1.00	10	694.4	140	2.84	19423.52



Network plane for zone
B - Brackish
Pipe numbers and flow
direction

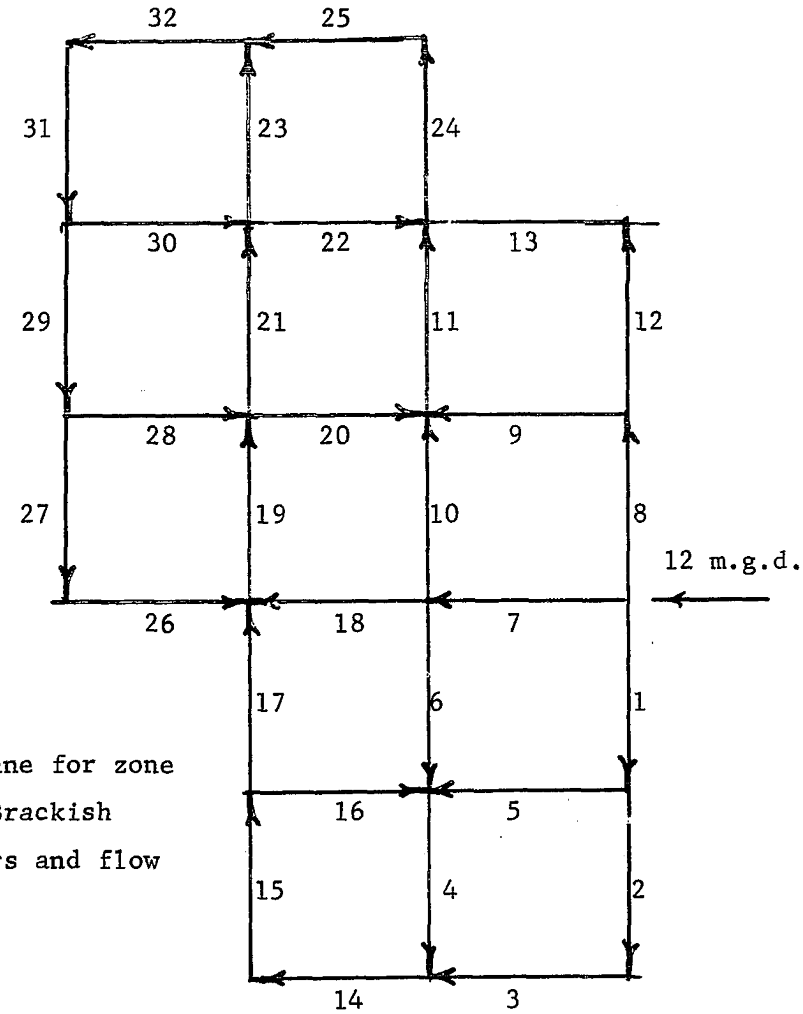
Figure 6

TABLE XXIV

NETWORK DESIGN

Supply C-B

Pipe No	Mgd	D Inches	Gpm	C	V ft/sec	L feet
1	4	18	2777.8	140	3.5	4593.4
2	2.2	14	1527.8	140	3.18	3937.2
3	2	14	1388.9	140	2.9	5905.80
4	.5	8	347.2	130	2.2	3281
5	.9	10	625	140	2.55	11811.60
6	1.0	10	694.4	140	2.84	9186.80
7	4	18	277.8	140	3.5	7874.40
8	4	18	277.8	140	3.5	3937.2
9	.5	8	347.2	130	2.20	7874.40
10	2.5	14	1736.1	140	3.76	6562
11	2.4	14	1666.7	140	3.48	5905.80
12	3	16	2083.3	140	3.32	5249.6
13	2.8	16	1944.4	140	3.10	5249.6
14	1.8	12	1250.0	140	3.55	6562
15	1.8	12	1250.0	140	3.55	10499.20
16	.5	8	347.2	130	2.22	7218.20
17	1.3	10	902.8	140	3.69	7874.40
18	.5	8	347.2	130	2.9	5249.6
19	1.3	10	902.8	140	3.69	5249.6
20	.100	4	69.4	130	1.78	5249.6
21	1.20	10	833.3	140	3.4	5905.80
22	.100	4	69.4	130	1.78	5249.6
23	1.100	10	763.9	140	3.12	5249.6
24	5.10	24	3541.7	140	2.71	4593.4
25	4.9	20	3402.8	140	3.55	5249.6
26	1.125	12	781.25	140	2.56	15748.8
27	2.5	16	1736.1	140	2.88	9186.80
28	2.5	16	1736.1	140	2.88	15748.8
29	5	20	3472.2	140	3.55	7874.4
30	.5	8	347.2	130	2.20	15748.4
31	5.5	24	3819.4	140	2.71	5249.6
32	6	24	4166.7	140	2.96	7874.4



Network plane for zone
C - Brackish
pipe numbers and flow
direction

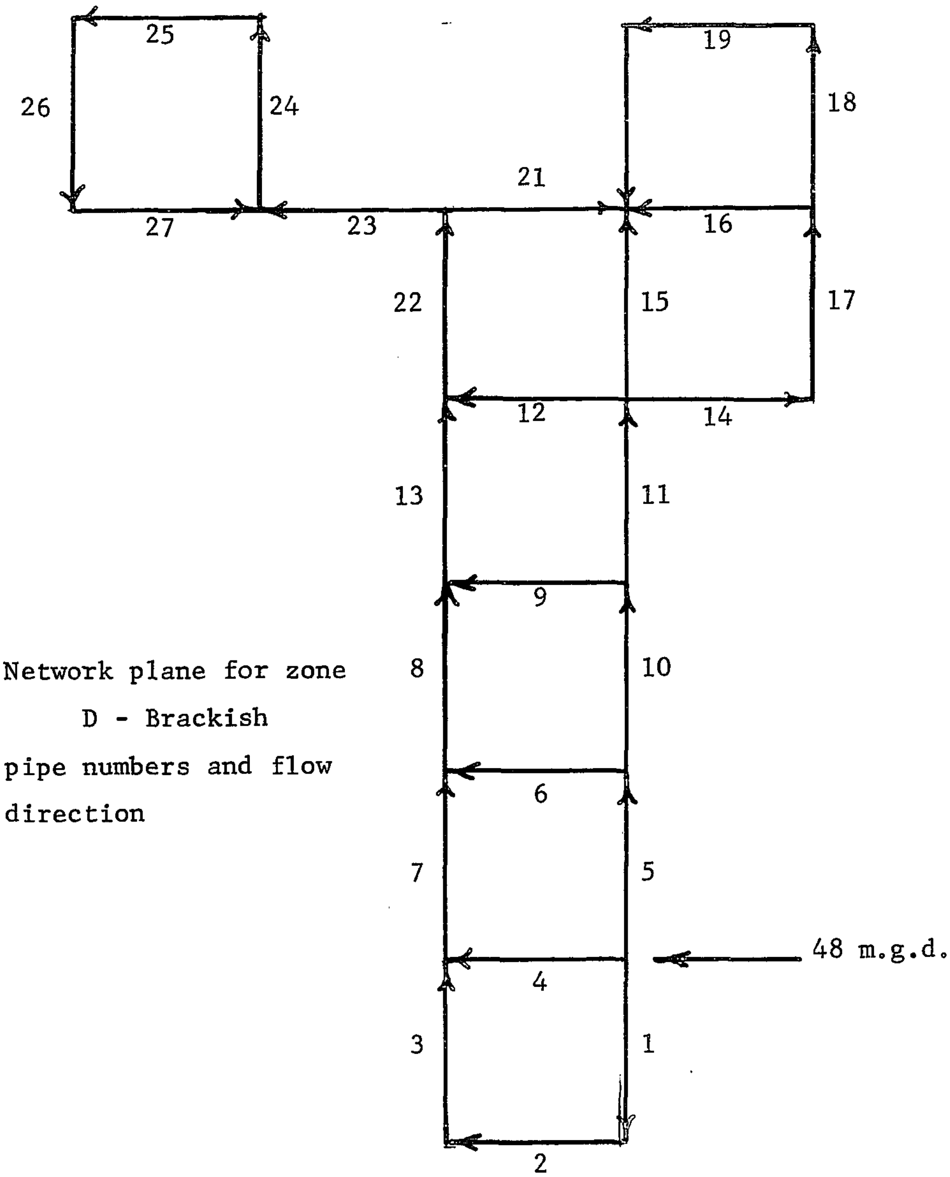
Figure 5

TABLE XXV

NETWORK DESIGN

Supply D-B

Pipe No	Mgd	D Inches	Gpm	C	V ft/sec	L feet
1	15	36	10416.7	140	3.28	7874.4
2	11	30	7638.9	140	3.47	6562
3	8	24	5555.6	140	3.94	21654.6
4	5	20	3472.2	140	3.55	11155.4
5	28	48	19444.4	140	3.45	15748.8
6	5	20	3472.2	140	3.55	7874.4
7	6	24	4166.7	140	2.96	5249.6
8	4	18	2777.8	140	3.5	1811.60
9	44	18	2777.8	140	3.50	15748.8
10	20	42	13888.9	140	3.22	7874.4
11	13	36	9027.8	140	2.85	14436.4
12	4	18	2777.8	140	2.96	13124
13	2	14	1388.9	140	2.9	14436.4
14	3.625	18	2517.4	140	3.50	23623.2
15	3.375	18	2343.8	140	3.07	13124
16	5.625	24	3906.3	140	2.96	23623.2
17	3.625	18	2517.4	140	3.50	14436.4
18	2.5	16	1736.1	140	2.88	10499.20
19	2	14	1388.9	140	2.9	15748.8
20	1.0	10	694.4	140	2.84	13124
21	1.45	12	1066.9	140	2.96	13124
22	2	14	1388.9	140	2.9	15748.8
23	.55	8	381.9	130	2.44	49871.2
24	.55	8	381.9	130	2.44	13780.2
25	.40	6	277.8	130	3.15	3937.2
26	.30	6	208.4	130	2.36	15748.8
27	.150	4	104.2	100	2.84	6562



Network plane for zone
D - Brackish
pipe numbers and flow
direction

Figure 6

WATER DISTRIBUTION SYSTEM PROGRAM

By Hardy Cross Method

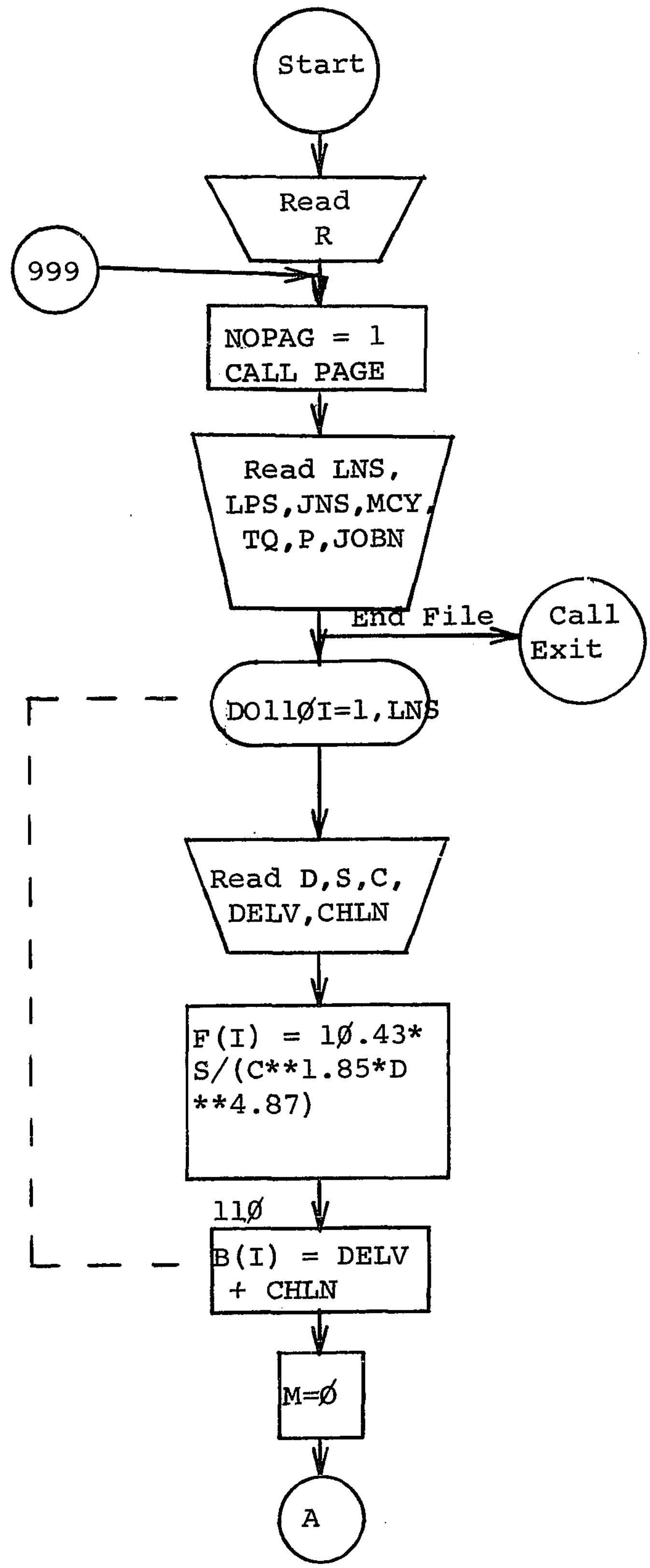
```
$JOB                              RS-Ø214Ø, RUN=CHECK, KP=29, TIME=3
          INTEGER R
          DIMENSION Q(1ØØ), QI(1ØØ),F(1ØØ),L(1ØØ),B(1ØØ),K(1ØØ)
          COMMON NOPAG,NOLIN
      1Ø  FORMAT (3I5,I6,2F6.1,2I6)
      2Ø  FORMAT (F5.1,4F8.1)
      3Ø  FORMAT (I5,2F9.1)
      4Ø  FORMAT (' ',9X,315)
      5Ø  FORMAT ('Ø',T11,15,2(5X,F9.1),4X,F9.1)
      55  FORMAT ('Ø',T11,15,2F9.1)
      6Ø  FORMAT (10X,'    N    NN JOBNO')
      7Ø  FORMAT ('Ø',T13,'LINE',T21,'INT. FLOW',T35,'COR. FLOW'
            ,T49,"HEAD L IOSS')
      8Ø  FORMAT (' ',T14,"NO.",T24,"GPM",T38,"GPM",T52,"FEET"
            //)
      9Ø  FORMAT (/ 1ØX,'  JCT PRESSURE PRES. HEAD')
     1ØØ  FORMAT (1ØX,'  NO.     PSI      FEET'/)
     22Ø  FORMAT (' ',T13,"NO. LINES', 15,". NO. LOOPS'15,'.
          NO. JUNC'15,'1.'/' ', T13,"MAX. CYCLES'15'.TQ'F6.
          1'.  PRESSURE'F6.1,'.'//)
     88Ø  FORMAT ( 'ØDQ -- ',F6.2)
   C      INPUT SECTION
          READ (1,1Ø) R
     999  NOPAG = 1
          CALL PAGE
          READ (R,1Ø,END=998) LNS,LPS,JNS,MCY,TQ,P,JOBN
          DO 11Ø I=1,LNS
          READ (R,2Ø) D,S,C,DELV,CHLN
          F(1) = 1Ø.43*S/((C**1.85)*(D**4.87)
     11Ø  B(1) = DELV + CHLN
          M = Ø
          DO 12Ø J=1,LPM
          READ (R,1Ø) KK,LPN
          K(J) = KK
          DO 12Ø MM=1,KK
          M = M+1
     12Ø  READ (R,1Ø) L(M)
          DO 15Ø I=1,LNS
          READ (R,3Ø) II,Q(I)
     15Ø  QI(I) - Q(I)
   C      ITERATION SEGMENT
```

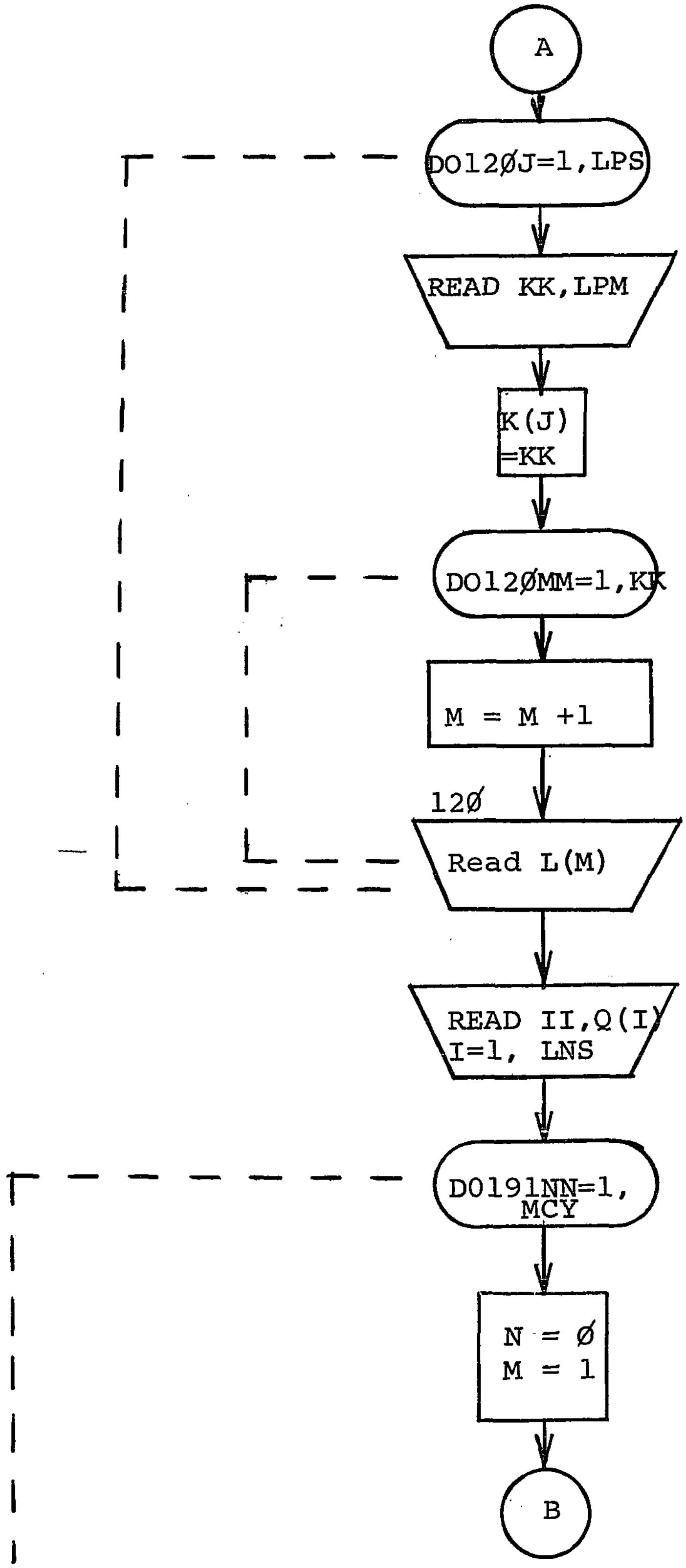
WATER DISTRIBUTION SYSTEM PROGRAM (Continued)

```
      DO 191 NN=1,MCY
      N = Ø
      M = 1
      DO 19Ø J=1,LPS
      S1 = Ø.Ø
      S2 = Ø.Ø
      KK = K(J)
      DO 16Ø MM=1,KK
      I = L(M)
      S = FLOAT(ISIGN(1,I))
      I = IABS(I)
      B1 = F(I)*ABS(Q(I))**Ø.85
      H = B1*Q(I)*S
      M = M+1
      S1 = S1+H
 16Ø  S2 = S2+B1
      IF (S2) 18Ø,18Ø,181
 181  DQ = Ø.54Ø5*S1/S2
      M = M-KK
      DO 17Ø MM=1,KK
      I = L(M)
      B1 = FLOAT(ISIGN(1,I))
      I = IABS(I)
      Q(I) = Q(I)-B1*DQ
 17Ø  M = M+1
      IF (DQ) 182,18Ø,182
 182  DQ = ABS(DQ)
      IF (TQ-DQ) 19Ø,19Ø,18Ø
 18Ø  N = N+1
 19Ø  CONTINUE
      IF (N-LPS) 191,192,192
 191  CONTINUE
 192  CONTINUE
C     OUTPUT DATA SEGMENT
      WRITE (3,22Ø) LNS,LPS,JNS,MCY,TW,P
 193  WRITE (3,6Ø)
      WRITE (3,4Ø) N,NN,JOBN
      WRITE (3,7Ø)
      WRITE (3,8Ø)
      NOLIN = NOLIN+1Ø
      DO 2ØØ I=1,LNS
      S = F(I)"ABS(Q(I))**Ø.85*Q(I)
      B(I) = B(I)+S
      NOLIN = NOLIN +2
```

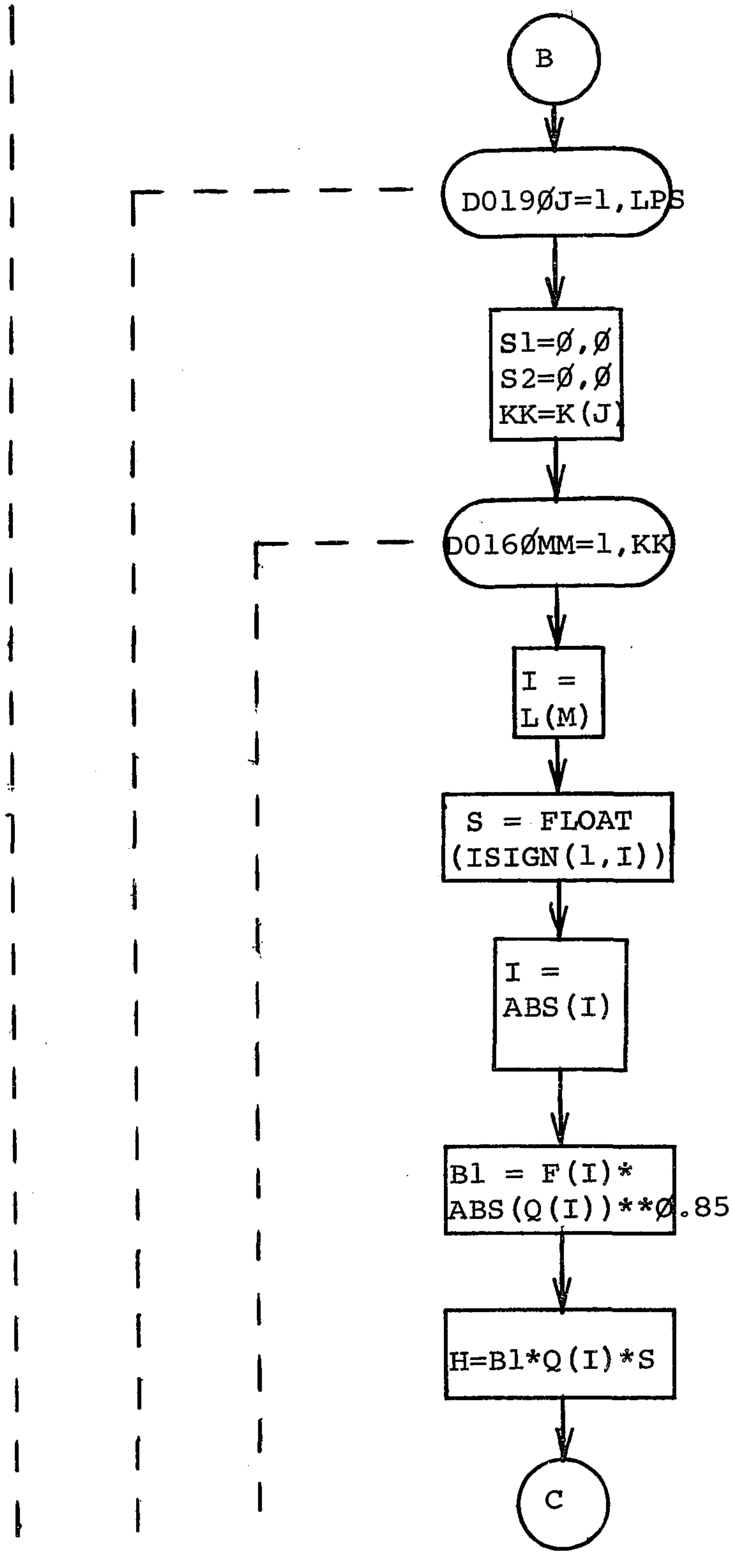
WATER DISTRIBUTION SYSTEM PROGRAM (Continued)

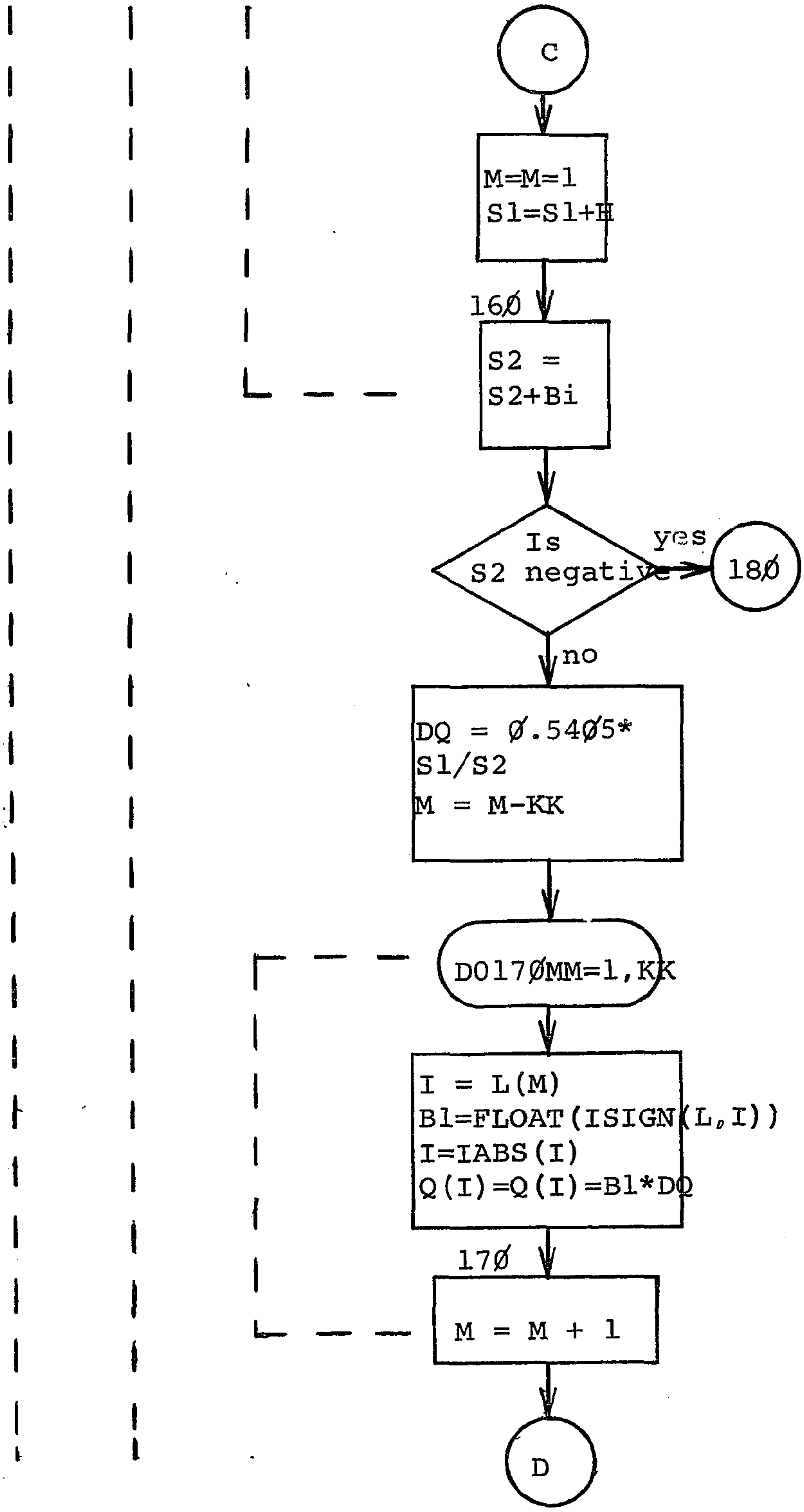
```
      IF (NOLIN-54) 2ØØ,2ØØ,2Ø1
 2Ø1  CALL PAGE
      WRITE (3,22Ø) LNS,LPS,JNS,MCY,TQ,P
      WRITE (3,6Ø)
      WRITE (3,4Ø),N,NN,JOBN
      WRITE (3,8Ø)
      WRITE (3,8Ø)
      NOLIN = NOLIN + 1Ø
 2ØØ  WRITE (3,5Ø) I,QI(I),Q(I),S
      WRITE (3,88Ø) DQ
      CALL PAGE
      WRITE (3,9Ø)
      WRITE (3,1ØØ)
      I = 1
      F(I) - 2.3Ø7*P
      WRITE (3,55) I,P,F(I)
      NOLIN = NOLIN+3
      DO 21Ø 1=2,JNS
      READ (R,1Ø) M,11,N
      F(M) - F(11)-B(N)
      P = Ø.433*F(M)
      NOLIN = NOLIN + 2
      IF (NOLIN-54) 21Ø,211,211
 211  CALL PAGE
      WRITE (3,9Ø)
      WRITE (3,1ØØ)
      NOLIN = NOLIN+3
 21Ø  WRITE (3,55) I,P,F(I)
      GO TO 999
 998  CALL EXIT
      END
      SUBROUTINE PAGE
      COMMON NOPAG,NOLIN
    1 FORMAT ('1',111X,'PAGE  ',13/)
      WRITE (3,1) NOPAG
      NOLIN = 2
      NOPAG = NOPAG+1
      RETURN
      END
```

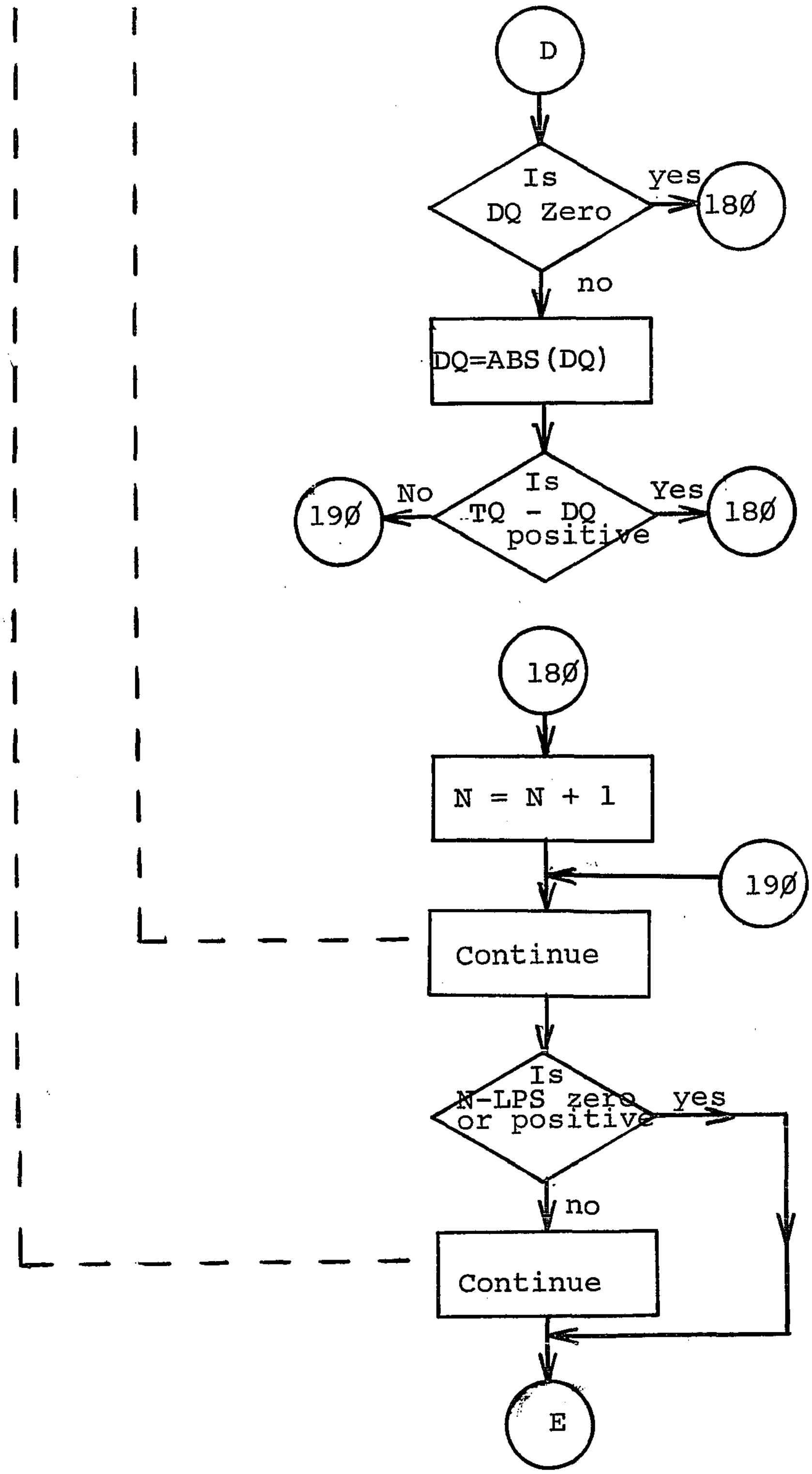

Start
Read
R
999
NOPAG = 1
CALL PAGE
Read LNS,
LPS,JNS,MCY,
TQ,P,JOBN
End File
Call
Exit
DO11ØI=1,LNS
Read D,S,C,
DELV,CHLN
F(I) = 1Ø.43*
S/(C**1.85*D
**4.87)
11Ø
B(I) = DELV
+ CHLN
M=Ø
A

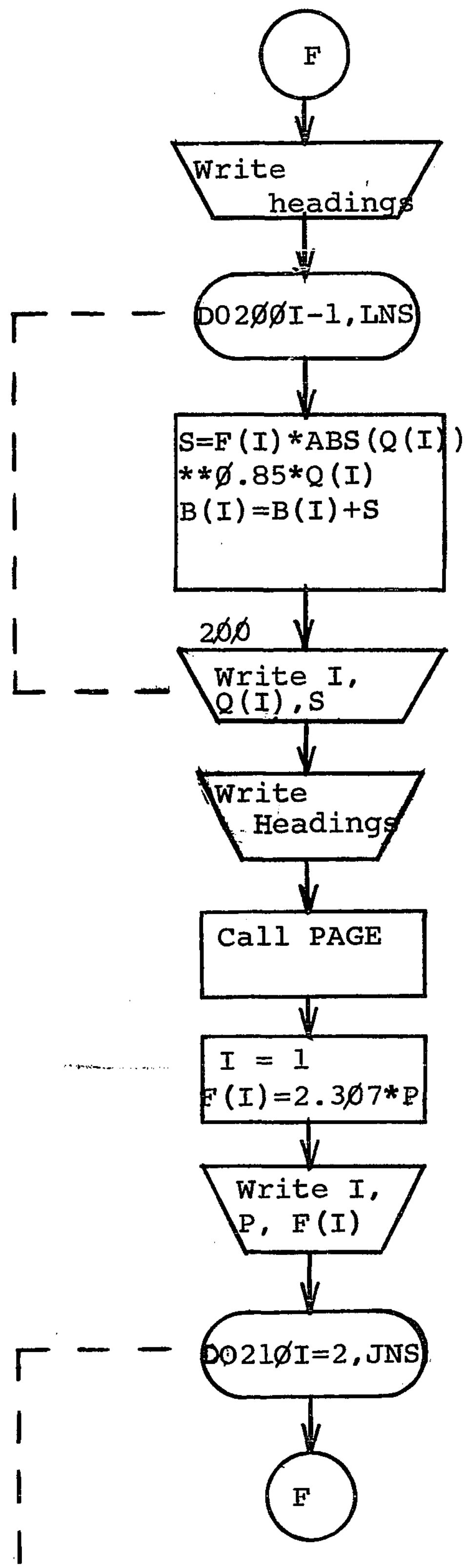


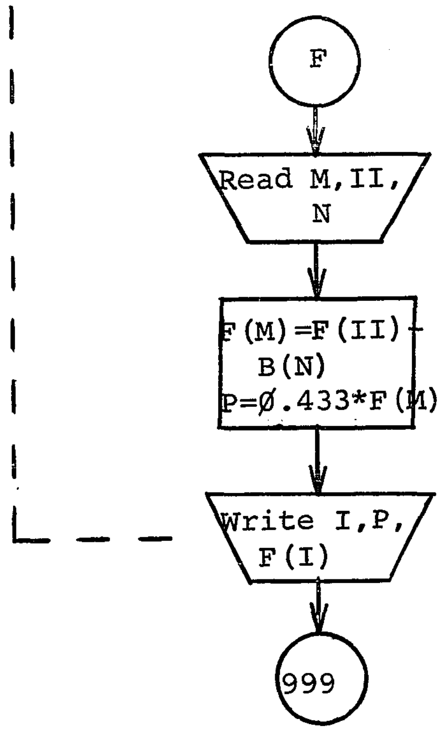
A
DO12ØJ=1,LPS
READ KK,LPM
K(J)
=KK
DO12ØMM=1,KK
M = M +1
12Ø
Read L(M)
READ II,Q(I)
I=1, LNS
DO191NN=1,
MCY
N = Ø
M = 1
B


B
DO19ØJ=1,LPS
S1=Ø,Ø
S2=Ø,Ø
KK=K(J)
DO16ØMM=1,KK
I =
L(M)
S = FLOAT
(ISIGN(1,I))
I =
ABS(I)
B1 = F(I)*
ABS(Q(I))**Ø.85
H=B1*Q(I)*S
C


C
M=M=1
S1=S1+H
16Ø
S2 =
S2+Bi
Is
S2 negative
yes
18Ø
no
DQ = Ø.54Ø5*
S1/S2
M = M-KK
DO17ØMM=1,KK
I = L(M)
B1=FLOAT(ISIGN(L,I))
I=IABS(I)
Q(I)=Q(I)=B1*DQ
17Ø
M = M + 1
D


D
Is
DQ Zero
yes
180
no
DQ=ABS(DQ)
Is
TQ - DQ
positive
No
190
Yes
180
180
N = N + 1
190
Continue
Is
N-LPS zero
or positive
yes
no
Continue
E


F
Write headings
DO2ØØI-1,LNS
S=F(I)*ABS(Q(I))
**Ø.85*Q(I)
B(I)=B(I)+S
2ØØ
Write I,
Q(I),S
Write
Headings
Call PAGE
I = 1
F(I)=2.3Ø7*P
Write I,
P, F(I)
DO21ØI=2,JNS
F



Subroutine PAGE