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Optimal allocation of effluent charges in regional water resource systems.

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University of Windsor

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OPTIMAL ALLOCATION OF EFFLUENT CHARGES IN REGIONAL WATER RESOURCE SYSTEMS

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
THROUGH THE DEPARTMENT OF INDUSTRIAL ENGINEERING
IN PARTIAL FULFILMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF APPLIED
SCIENCE AT THE UNIVERSITY OF WINDSOR

BY

MOHAMED EL MOUGY AHMED

Faculty of Graduate Studies

University of Windsor
WINDSOR, ONTARIO, CANADA

1979

ABSTRACT

Environmental resources play a major role in economic systems through the service they provide to assimilate or carry away the residuals of production processes. As water resources have become scarce to offer their service to the growing number of population, urbanization, and economic activities, the optimal allocation of their assimilative capacities among the users can be achieved through the forces of the market system. The effluent charges strategy attains this objective. The strategy, in effect, imposes a price on the use of the water resource and thus provides an incentive to the polluters to seek the most efficient waste treatment methods.

A mathematical model is developed to determine, within the framework of a regional water quality management system, the optimal effluent charge rates to be levied against all polluters in a river basin. In addition, the model determines the optimal treatment policy for each polluter such that the required water quality standards in the basin are satisfied at a minimum total cost.

The formulation of the model reflects the presence of a large number of factors which account for the variations in stream characteristics as well as in plant performance at each pollution source. The factors interact with each other through complex, nonlinear transfer functions. Consequently, the objective function and constraints are highly nonlinear

in nature, which calls for a nonlinear optimization method to find the solution. The Sequential Unconstraint Minimization Technique (SUMT) has been used for this purpose.

Two main features distinguish the present model from previous works. First, the attainment of water quality standards throughout the basin is ensured by explicitly specifying the appropriate constraints in the model. Second, the model determines the effluent charges as a set of nonlinear rates as opposed to a set of uniform rates obtained by the existing models.

The model is applied to two different cases, and the results are interpreted in the context of the complex interactions among all the factors involved. The results point out the importance of developing complex mathematical models in order to deal with complicated problems of environmental pollution.

I wish to dedicate this work to

my parents

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BOD - Biochemical oxygen demand

C - Concentration level of dissolved oxygen, mg/ℓ

CS - Saturation concentration level of DO, mg/ℓ

CU - Upstream concentration level of DO, mg/ℓ

DO - Dissolved oxygen

EP - Phosphorus concentration level, mg/ℓ

F - Total value of the objective function

FC - Charge cost function

FT - Waste treatment cost function

F1 - A conversion factor; $\frac{day.ft^3.mg}{sec.lb.\ell}$

G - Constraint function

K_1 - Biological oxidation rate coefficient; day^{-1}

K_2 - Rearation rate coefficient; day^{-1}

K_3 - Sedimentation or absorption rate coefficient of BOD; day^{-1}

L - Concentration level of biochemical oxygen demand, mg/ℓ

La - Local BOD runoff rate; mg/ℓ/day

LB - Maximum BOD content at the beginning of the zone, mg/ℓ

LE - Stream BOD content at the end of the zone, mg/ℓ

LU - Upstream concentration of BOD, mg/ℓ

MAXBOD - Maximum allowable BOD level in the river, mg/ℓ

MAXPHR - Maximum allowable phosphorus in the river, mg/ℓ

MDO - Minimum DO concentration level in the river, mg/ℓ

MGD - Million gallons per day

MINDO - Minimum allowable DO level in the river, mg/ℓ

P - Modified objective function in SUMT formulation

PH - Maximum phosphorus content in the river, mg/ℓ

<P-R> - Rate of photosynthesis minus the rate of respiration, mg/ℓ/day

PU - Upstream phosphorus concentration, mg/ℓ

Q - Stream flow rate; cfs

$\bar{Q}$ - Average daily flow of the plant, MGD

QU - Upstream flow rate, cfs

r - Constant value in SUMT formula

T - Stream temperature, ^{o}K

WB - Amount of organic waste produced at pollution source, lb/day

WP - Amount of phosphorus waste produced at pollution source, lb/day

X - BOD treatment level applied in the theoretical functions

y - Effluent charge rate, $/lb of BOD

Z - Phosphorus treatment level applied to the empirical functions

θ_1, θ_2 - Parameter coefficient for effluent charge rate

τ - Residence time, in days from source of pollution

CHAPTER I

INTRODUCTION

1.1 Economic Aspects of Environmental Pollution

The quality of water, air, and soil, is affected by the economic activities of human beings to the extent that most researchers consider the pollution problem as a phenomenon related to production and consumption processes, (Dales, 1968). This relationship can be clearly shown by tracing the pollution to its primary sources.

Men, through their daily activities, take from the environment a wide variety of materials, agricultural products, and animal materials. They transform them into many varieties of economic goods. During the transformation processes, many unwanted materials - solid, liquid or gaseous - are generated and discarded into the environment as residuals. Some of these residuals are harmful (toxic chemicals, for example) and could damage the environment; some others are harmless, but they could react chemically with other substances or with each other in the air or water in a damaging way (as in the sunlight). On the other hand, the final economic goods are eventually consumed, a process during which they undergo physical or chemical transformation and become unwanted materials. Sooner or later they will be discarded again.

If the environmental capacity to absorb or to carry away all the residuals was unlimited, there would be no pollution problem and residuals could be discharged into water, air, or soil without limit. In earlier days, a smaller, more dispersed population, and a much lower level of economic activity did not generally impose a real load on the capacity of the environment to assimilate residuals. Environmental resources were in such abundance that they seemed to have an unlimited capacity to assimilate the wastes. Most economists at that time were considering these common resources as perfect examples of free goods. But, as population, urbanization, and economic activity have grown, what were once plentiful environmental resources have become increasingly scarce, and can no longer be fully available to the increasing number of users.

It is clear that the amount of discarded waste depends on two factors: number of people in the economy (population density), and per capita consumptions of materials. Environmental degradation, therefore, will increase with increasing population and economic growth. Assuming the society has no intention to halt or decrease the economy's growth, it has only one alternative left to control pollution, that is to seek new technical methods of pollution abatement to decrease the rate of waste residuals per throughput of raw materials.

On the other hand, eliminating the discarded wastes, which are unwanted residuals with no value, will cost the society at large. The dischargers, however, are under no obligation to incur this cost or even economize in their use of natural resources as waste receptors. This has created a situation in which the costs of production and the prices of goods and services diverge, in different degrees, from the true costs of production. Such divergence not only leads to a misallocation of the employed resources, but can also result in a deteriorating environmental quality (Ralph, 1963).

Two points emerge from this analysis. First, the environmental resources play an important role in the economic system through the service they offer to the production processes to carry away or assimilate rssiduals. The concept of the economic system should be broadened to include these resources as a counterpart to such other factors in the production processes as capital, labour, and materials, (Ingemar et al, 1977). Figure 1.1 diagramatically depicts this concept. Second, any real effort to control pollution would have to provide a set of strong economic incentives to persuade dischargers to seek these new, technical methods of pollution abatement.

In order to alleviate this situation, environmental quality management should be considered as a resource allocation problem; that is, environmental resources, like all other scarce resources, should be optimally allocated among the different competing users so as to maintain a desired level of environmental quality. Although the free market system provides the mechanism for optimal allocation of resources, in the case of environmental resources it could fail. The failure may be due to either the lack of property rights, or the public good nature of these resources.

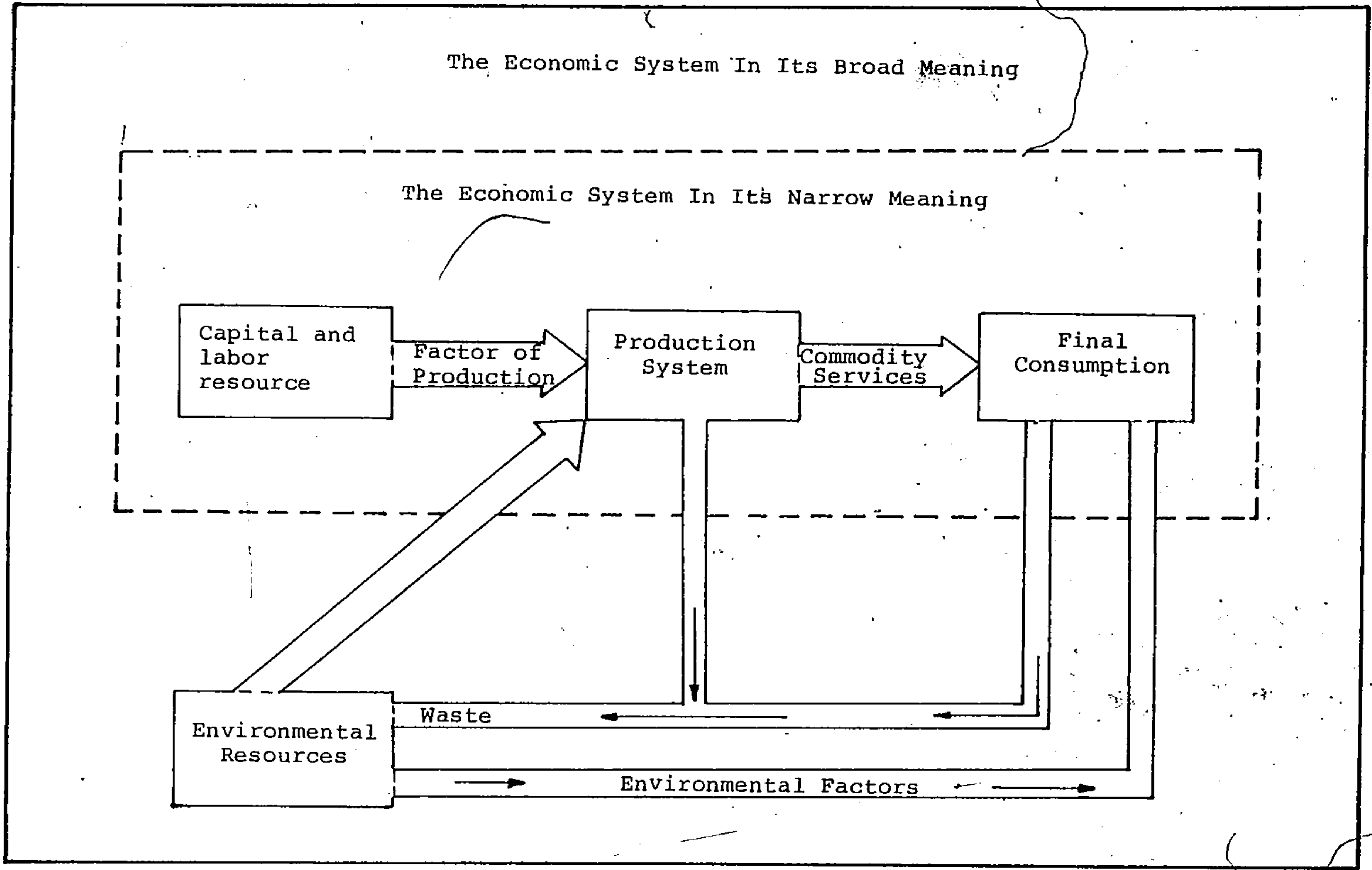

Figure 1.1 Economic system including environmental resources as a factor in the production processes (Ingemar *et al*, 1977).

To overcome the market failure for the environmental resources, some form of governmental intervention is suggested for maintaining the desired environmental quality levels, and achieving the optimal allocation of resources among different users (Kneese, 1964). The government agency may use the strategy it deems best to fullfil its responsibility. Such methods as the regulation enforcement and subsidies have been widely used in the past one-and-a-half decades. The regulation enforcement strategy imposes discharge levels on firms and municipalities, whereas the subsidies method provides monetary grants for constructing waste treatment facilities. In spite of these efforts, both strategies have failed to bring about the desired levels of environmental quality (Alexander, 1976). The reason lies in the fact that both strategies have two characteristics which render them costly and ineffective. First they rely greatly on detailed information and procedures which are difficult to obtain and apply. Second, they lack economic incentives to realize the social cost of degrading the environment.

The effluent charge strategy is an alternative control policy, and it has the potentiality to overcome the drawbacks inherent in the other two methods. The strategy requires that those who use the environmental resources pay for them at a price that reflects their scarcity. Pricing the environmental resource tends to establish, among the different users, an optimal allocation pattern of these resources. The strategy is simple and applicable; besides, it places greater reliance on the self-motivation of dischargers to reduce their waste.

1.2 The Purpose and Plan of Study

The primary purpose of this investigation is to develop a mathematical model of water pollution control, which would determine the optimal effluent charge rates to be levied against all the polluters in a river basin system, such that the desired water quality levels in the basin are maintained at a minimum total cost.

In Chapter I, the pollution problem has been embedded in an economic framework; since the problem has arisen in the context of economic activities, its solution may be found in economic theory.

Chapter II presents the technical aspects of the water pollution problem. The competing uses of water resources, are discussed and the sources of pollution and pollutant types are presented. The measures of water quality used in the study are discussed next. Finally, the technical options for water pollution control are exhibited, emphasizing conventional waste treatment methods.

Chapter III is devoted to an evaluation of the effluent charges strategy as an alternative control method The role played by the price mechanism, through the market function, to solve the problem of resource allocation is discussed. The reasons for market failure in the case of the environmental resources, and the use of effluent charges to overcome this failure are explained. A comparison is made between the effluent charge strategy and the other two strategies with respect to three important criteria: effectiveness, flexibility, and efficiency. Finally, the criticisms of, and the misunderstanding about, the strategy are evaluated.

In Chapter IV, the historical evolution of the effluent charge strategy is presented in two parts. In the first part, works carried out to date on the development of theoretical bases for the strategy are discussed. The second part offers a survey of the studies dealing with applications of the strategy within framework of water quality management models.

In Chapter V, the mathematical model of the river basin system is developed. The river is divided into a number of zones, each receiving wastes from municipal and/or industrial sources located along the river. Water quality measures are defined and a modified form of the Streeter-Phelps equations, as suggested by Dobbins (1964) are employed to predict the behaviour of these measures at various points of a zone. The model's objective function consists of the treatment costs as well as the effluent charges levied against the untreated portion of the wastes. The constraints of the model define the allowable levels of water quality measures in each zone. The model is highly nonlinear in nature, calling for a nonlinear optimization method to find the solution.

Chapter VI considers the application of the optimization model in two different cases. The first assumes that the river receives waste from municipal sources. The cost function employed in this example are derived from actual data collected, during the period 1975-1977, from municipal wastewater treatment plants in Southern Ontario The second example assumes that the river receives waste from different municipal and industrial sources. The cost functions employed are based on the current information on the cost of industrial and municipal waste treatment.

Chapter VII is devoted to discuss the results of the optimization model as it is applied in the two cases. The discussion is followed by drawing a number of conclusions for the present investigation . Proposals are made, at the end of the report, for further research and studies.

CHAPTER II

TECHNICAL ASPECTS OF THE WATER POLLUTION PROBLEM

2.1 Introduction

For the water to be useable, it should possess certain quality levels. Over the years, highly technological treatment methods have been developed to improve the quality of water in rivers and streams. Yet, there are some questions regarding the effectiveness of these methods to cope with increasing problem of water resource pollution.

The chapter discusses, first, the various uses of water resources; second, it identifies the different categories of waste discharges, and explains the measures of water quality. Some technological options for reducing the amount of waste discharge without a decrease in economic growth are presented. Finally, the conventional waste treatment methods - primary, secondary and tertiary - are briefly discussed.

2.2 Importance of Water Resources

The importance of water resources (e.g., streams, rivers, and lakes) can be assessed through the values of their three main services:

1) Value in Use: Water is withdrawn from the stream to satisfy domestic, industrial, and agricultural needs.

2) Value in Commerce and Recreation: The stream

serves as a means of transportation, a source of power, or a place to fish, boat or swim; it contributes to the environment, which makes a community a pleasant place to live in.

3) Value as a Waste Carrier: Stream flow may be used to carry waste materials away from their sources.

The first two functions compete with the third. If the amount of waste discharged into the stream is greater than the capacity of the stream to assimilate it, pollution problem will arise, and the value of the water course for its other two uses will reduce (Lee, 1970).

The threat to water quality arises mainly from discharging wastes from domestic, industrial, agricultural, and recreational activities into the water. These wastes can be grouped in various ways. One common classification differentiates between non-degradable and degradable wastes:

i) Non-Degradable Wastes: The sources of non-degradable substances are mainly inorganic chemicals such as chlorides, synthetic organic chemicals and inorganic suspended solids. Some industrial wastes contain inorganic or metallic salts and synthetic organic chemicals. Domestic water use results in a small increase in the content of chlorides and other dissolved salts. The return flow from irrigation is generally significantly higher in dissolved salts than the inflow water. Also, some other discharges from mines may contain copper, zinc, and uranium. Many of these non-degradable wastes may be toxic or corrosive. Some of them may impart color or taste to the water. Suspended materials and colloidal matter cause turbidity in surface waters. This not only makes water less attractive, but can also damage fish life, and inhibit the growth of some aquatic plants such as algae which may or may not be desirable. Non-degradable wastes are usually diluted and may be changed in form, but they are not appreciably reduced in weight in the receiving water (Kneese, 1964).

ii) Degradable Wastes: Degradable wastes include thermal wastes and organic wastes which come mainly from domestic, industrial and agricultural operations. These types of waste are subsequently decomposed into harmless substances by the stream's natural biological, chemical, or physical processes, which result in a significant weight reduction of the waste load. The concentration of a degradable waste, however, is much more difficult to be determined than a non-degradable waste because the capacity of the stream to decompose (or to assimilate) the waste is determined by many factors such as stream flow, stream temperature, and the physical and biological properties of the stream that affect the rates of settling and reaeration (Lee, 1970) Thermal loads are classified as degradable waste since the heat is dissipated in receiving waters, primarily by evaporation and conduction in ground waters. The primary sources of thermal wastes are the generation of electrical energy and the cooling operations in many industries (Fan, et al, 1973).

2.3 Water Quality Measures

A measure of organic waste load is Biochemical Oxygen Demand (BOD), which is a measure of the amount of oxygen needed to oxidize a unit of organic waste material into relatively harmless components. The amount of oxygen demanded and the rate at which it is drawn upon are mainly functions of the quality of the waste, its chemical characteristics, as well as the temperature of the receiving water. For example, toxic substances may appreciably reduce the rate of decomposition by inhibiting bacterial action. At higher temperatures, where the oxygen saturation level of water is relatively low, bacterial action is accelerated, and dissolved oxygen in the water is drawn upon more rapidly (Davidson and Bradshaw, 1967). The imbalance between available oxygen and oxygen demand may proceed to the point of depleting the oxygen level in the stream completely (anaerobic conditions). Such conditions are most likely to occur in the summer, when streamflows tend to be low and temperatures high. All the efforts to control water quality have to avoid such conditions. In fact, the rate at which "BOD" is depleted (which depends on the amount of waste at the point of discharge) combined with the rate at which oxygen is restored, determines the level of Dissolved Oxygen (DO) in the stream.

The combined effect of organic waste discharged at a specific location and reaeration in the stream results first in a decrease and then in an increase in DO as the waste is carried or moved downstream. This phenomenon is illustrated by a characteristic curve known as the "oxygen sag" curve. In Figure 2.1, the variations in BOD concentration and the associated oxygen sag curves for two different levels of waste load discharge are presented. In Figure 2.1(a) the waste load is below the river's assimilative capacity, and thus a minimum level of "DO" is maintained throughout the stream. However, if the receiving waters are loaded excessively such as in Figure 2.1(b), the process of degradation will proceed anaerobically by the action of bacteria not utilizing free oxygen. Anaerobic processes produce hydrogen sulfide and other gases which have an annoying odor. These, combined with floating materials and sewage solids, are likely to be unpleasant from aesthetic and recreational view points. The bacteria content also makes the stream unsafe for water sports. However, the most direct impact of an excessive organic waste load in the stream is its effect of reducing the amount of "DO" to the point where most species of fish are unable to survive (Kneese and Bower, 1968).

Among the factors contributing to the degradation of water quality are plant nutrients, primarily phosphorus. Although nutrients themselves are not harmful to the water (except when they are present in excessive amounts) they can lead to intense algae growth, or "eutrophication", which, in general, is detrimental to aquatic life (Bishop, 1975). This is of particular importance in quiet waters

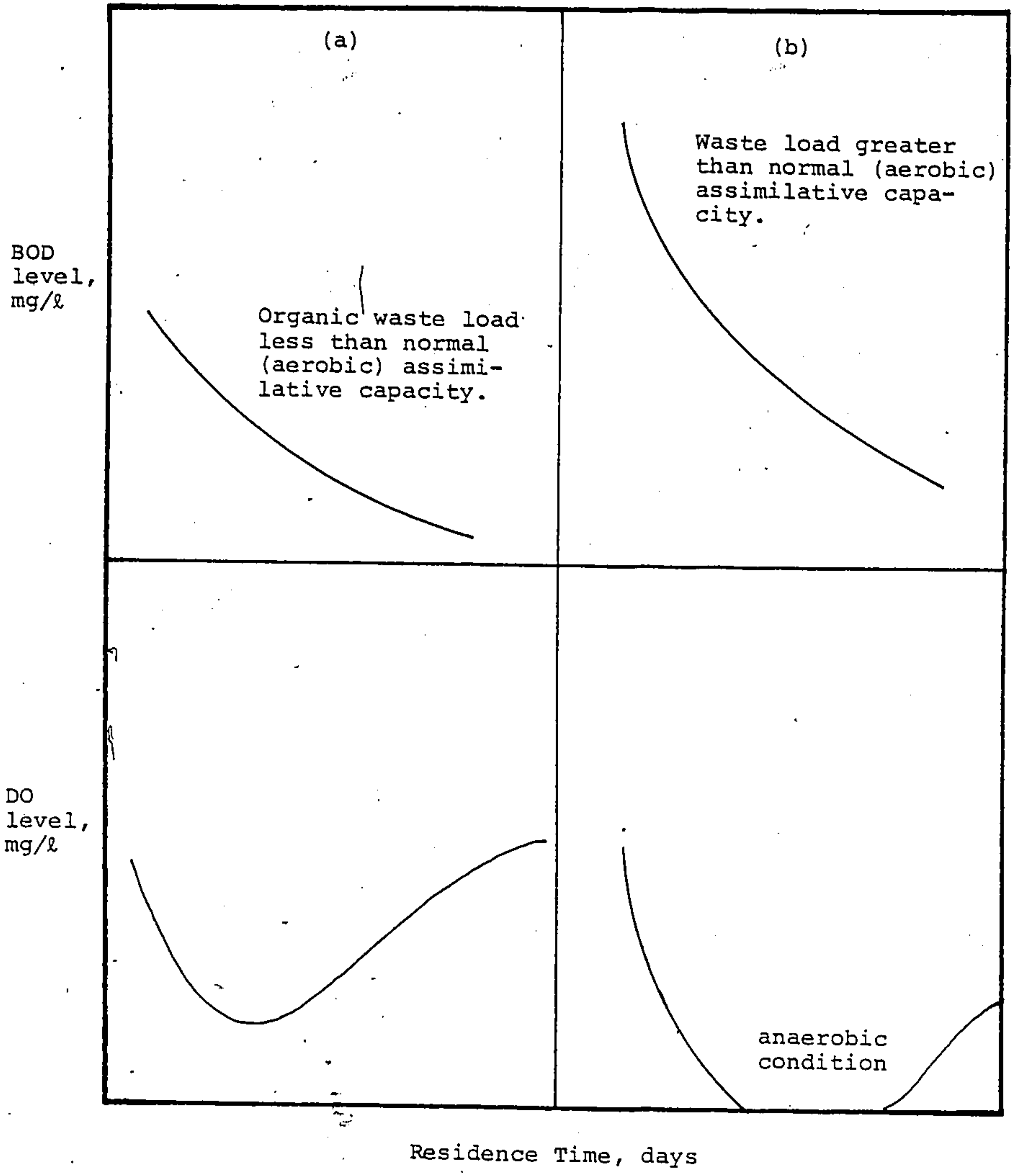

Figure 2.1. Schematic diagram of oxygen sag for two different levels of organic waste load, [Kneese, 1964].

such as lakes, bays, and estuaries. Since most lakes are considered as sinks for rivers, the maximum level of phosphorus substances in rivers should be controlled to prevent eutrophication processes, not only in rivers, but also in lakes.

2.4 Technological Options for Water Pollution Control

The quality of water resources can be improved in two ways (separately, or in combination): first, by making better use of the stream's assimilative capacity, and second, by reducing waste load discharges (Kneese and Bower, 1968).

As far as the first option is concerned, assimilative capacity can be enhanced in various ways. For instance, since the effect of waste discharge depends on the time and/or place of discharge, any change in one or both factors could affect pollution concentration. Some locations along the stream are better suited for carrying away and assimilating the waste than others. Alternatively, discharges can be timed to coincide with periods of maximum stream flow rate, and to avoid periods of high temperature. The assimilative capacity can also be increased by means of artificial reaeration, or by constructing dams to store and release water to dilute wastes during periods of low flow (low flow augmentation).

As for the second option, the reduction of waste load discharges can be accomplished in two broad ways:

(i) by reducing the generation of wastes per unit output,

(ii) by modifying the residual waste after generation.

Within these two broad categories a variety of techniques are available. In the first category, waste generation per unit output could be reduced by changing the types of raw material inputs or by modifying production processes in such a way as to increase the technical efficiency of materials used, which eventually results in less waste. Another possibility is to shift the economic activities toward more durable products. In the second category, the waste reduction could be accomplished either by material recovery or by waste treatment. Material recovery is now technologically possible for most types of material, such as paper, metal, and glass.

Water pollution can also be reduced by various techniques of waste treatment. There are a number of advanced waste treatment methods, capable of significantly reducing the harmful effects of waste discharge. However, the costs entailed in achieving such treatment levels are usually high, compared to other methods, which in many cases embody also a more effective means of waste reduction (Kneese & Schultze, 1975). Nevertheless, most policies have rested almost exclusively on the waste treatment approach to water pollution control. This may be due to the fact that waste treatment is the only general method for reducing waste discharges from different sources, e.g., households, industries, and mines. On the other hand, the absence of an adequate incentive to motivate the firms to search for alternative methods of waste reduction (such as recycling or material recovery) may also have contributed to this exclusive dependence on waste treatment techniques. In the next section, a brief discussion regarding the conventional treatment methods of domestic and industrial wastes and their economies will be given.

2.5 Conventional Methods of Waste Treatment

Conventional treatment of domestic and industrial wastes is a comparatively standardized process that can greatly reduce, but not eliminate, BOD level. The process involves the following steps:

i) Primary Treatment: In this stage the large solids are removed by screening and sedimentation processes. This step usually produces a wet, difficult-to-handle sludge which is usually digested in heated anaerobic tanks before final disposal. When waste treatment plants are operated adequately, the primary treatment of an influent containing organic wastes can reduce the first stage BOD by 35% to 45% (Kneese, 1964).

ii) Secondary Treatment: This stage is biological in character and essentially controls and accelerates the oxidation processes. Two major techniques are presently used, with various modifications. One is the trickling filter in which a biological film is grown on rocks or some type of plastic medium, and waste is applied intermittently, allowing air contact with the surface of the film. The other technique is the activated sludge process, in which air or oxygen is forced into a tank containing a mixture of waste and actively feeding biota. Part of the settled sludge containing the biota is recirculated and mixed with the entering waste in the aeration chamber.

Primary and secondary treatments combined usually can reduce BOD by between 80% and 95% (Kneese, 1964).

iii) Tertiary Treatment: Secondary treatment plant effluents can create some undesirable conditions in receiving streams through adverse effects on the dissolved oxygen levels, which result in unwanted changes in the living organisms of the stream and the possible excess growth of algae and other aquatic plants. To arrest these conditions, an advanced type of "tertiary" treatment is being developed as a third stage to follow conventional secondary treatment processes for further reduction of BOD as well as nutrients (such as phosphorus substances) which algae utilize for growth. This third stage can usually reduce the BOD level up to 99%; however, there is no typical tertiary treatment form. This third stage must be adapted to the particular needs of the receiving water concerned. Figure 2.2 illustrates the three conventional treatment stages.

Treatment costs in any plant increase rapidly as the removal of BOD is pushed upward, (Fig. 2.3). This has been confirmed by studies of many industries and different kind of pollutants. Kneese and Schultz (1975) demonstrated the relationship between the percentage of pollutants already

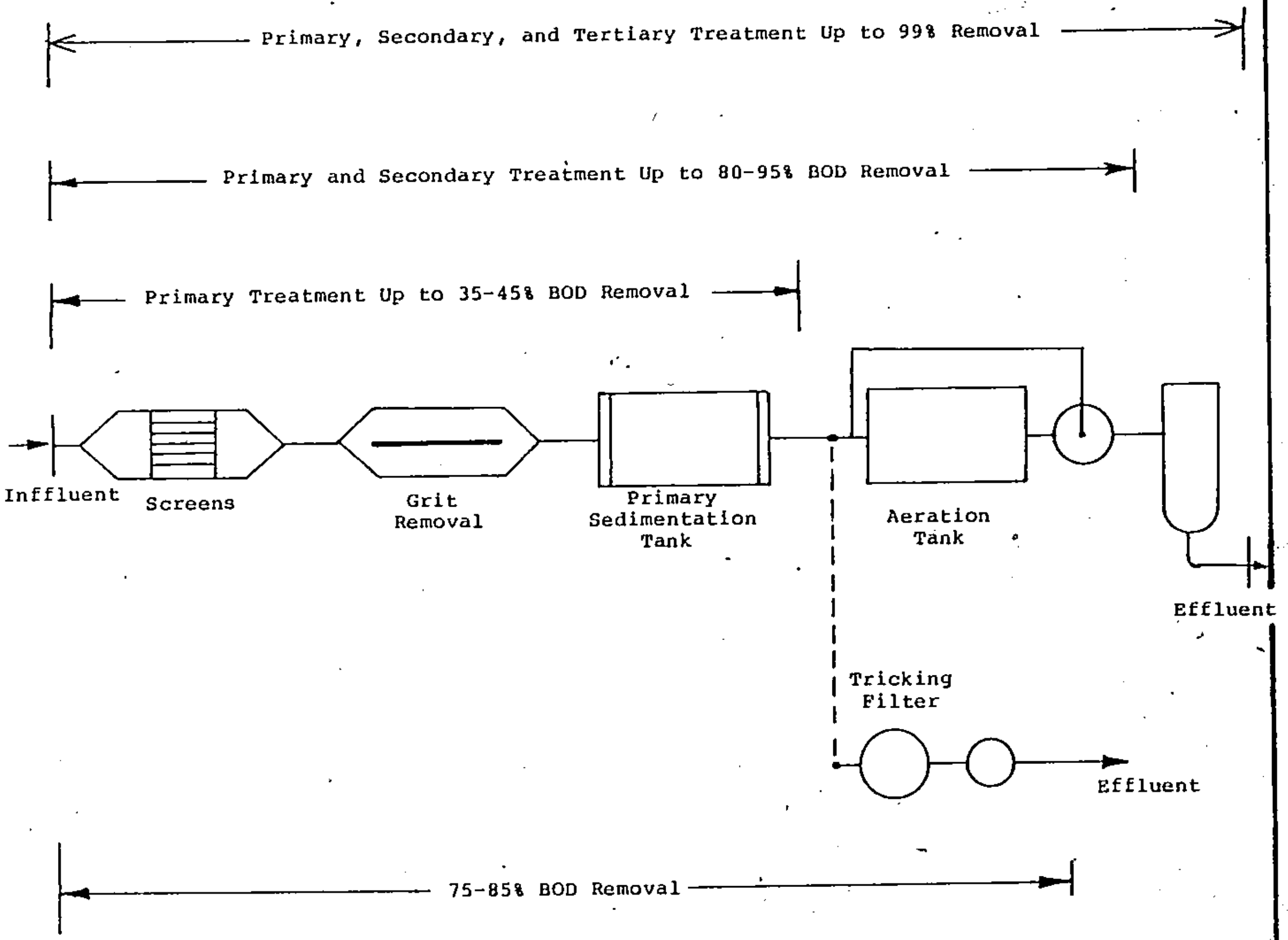

Figure 2.2 Conventional Waste Treatment Processes.

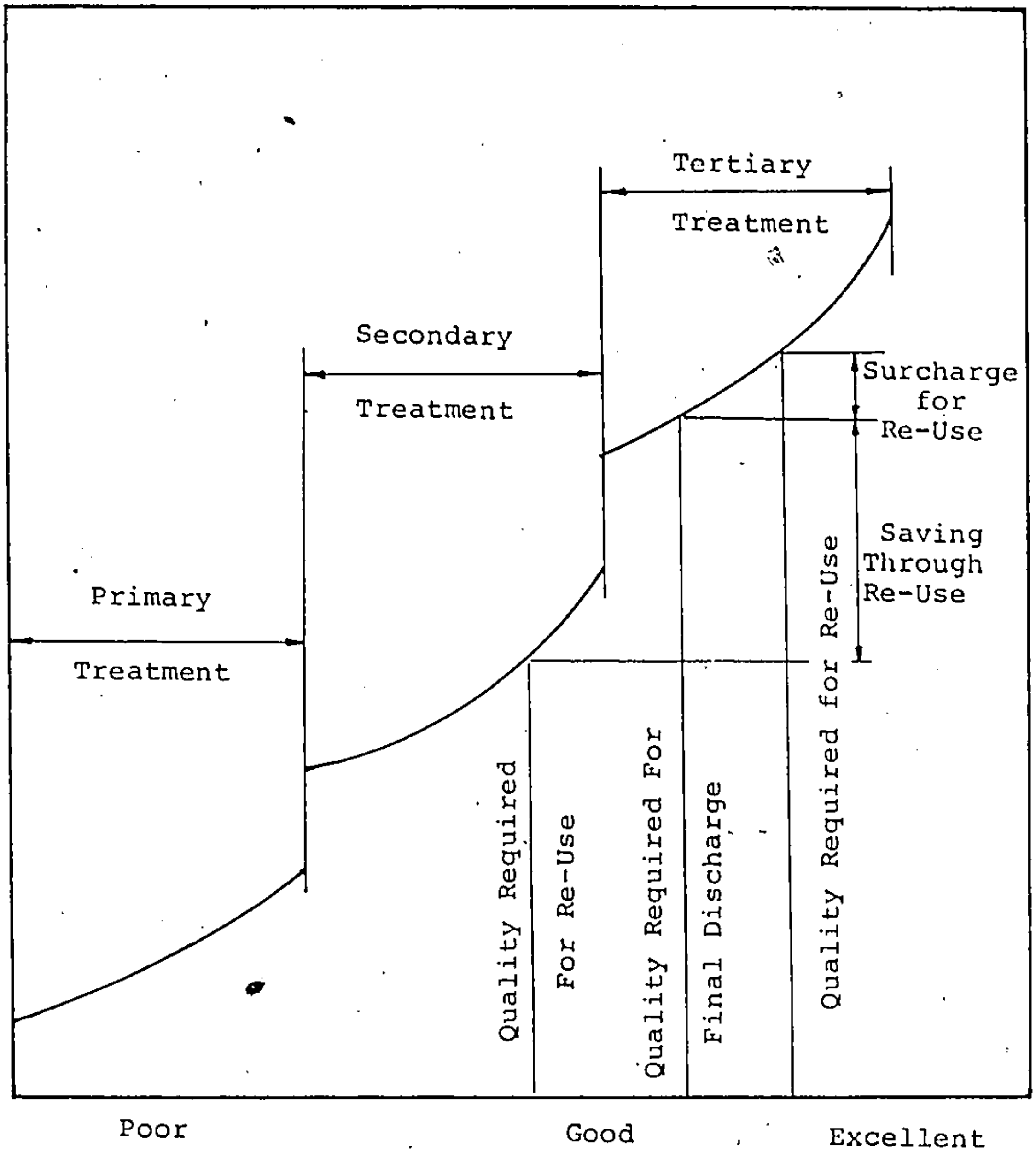

Figure 2.3 Quality of Effluent from Wastewater Treatment Plant (Eckenfelder and and Barnard (1971).

removed and the cost of removing an additional unit. The examples included beet sugar industry, meat-processing plants, and the petroleum refining industry, see Figure 2.4. These examples also illustrate another aspect of the pollution control costs, namely, that they differ widely from industry to industry; the incremental cost of removing pollutants above the 90 percent level is $0.05 per pound of BOD in beet sugar industry, $0.60 per pound for meat processing plants, and $0.22 per pound for petroleum refining industry.

On the other hand, within the same industry, individual firms may incur quite different treatment costs, depending on the magnitude of the waste flow they are handling. The studies given by Shah (1970), and Michel (1970) indicate that as the amount of waste flow increases, the per unit costs of capital invested plus operation and maintenance decreases, see Figure 2.4. This result is valid for both municipal and industrial waste treatment plants.

The differential between the pollution removal costs of municipal and industrial plants underlines a significant feature that a flexible pollution control policy should possess. That is, these policies must recognize and exploit these cost differentials so as to encourage the largest reduction in pollution from the firms with the smallest removal costs. This tends to minimize the total cost of pollution control by a greater amount than if uniform regulations of reduction were imposed on discharger, Kneese and Schultze (1975).

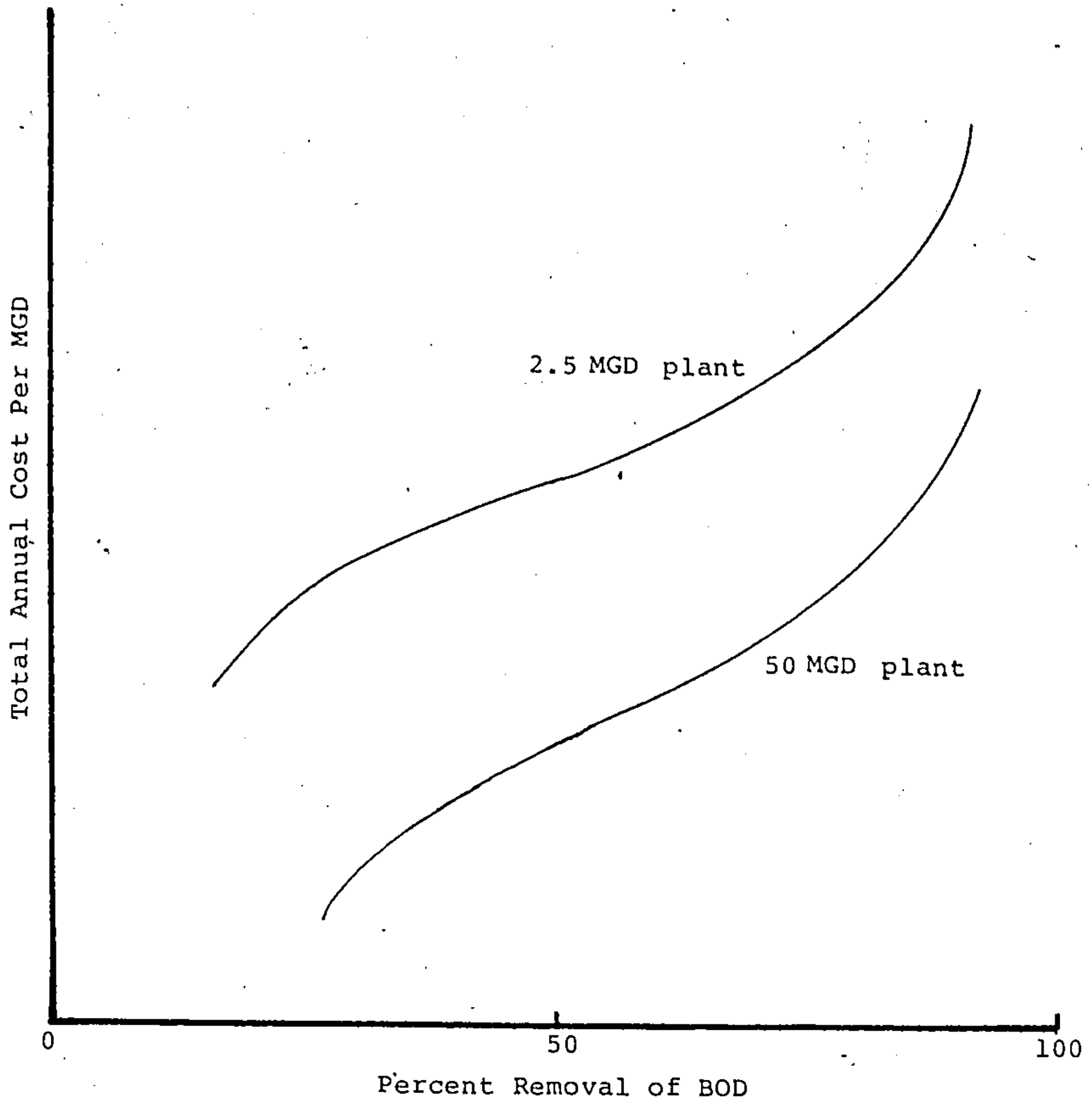

Figure 2.4 Relationship between degree of BOD removal and amount of waste flow in mgd and total annual cost per MGD. Kneese (1964)

CHAPTER III

THE EFFLUENT CHARGE AND WATER POLLUTION CONTROL

3.1 Introduction

Water resources have served as free goods and been considered as infinite sinks for the purpose of waste disposal. In an economic sense, goods or services are not free (scarce) when all users cannot be fully satisfied at Zero price (Beckerman, 1975). Nevertheless, when a firm, for example, discharges its pollutants into a stream, it is depriving the community, surround the waterway, of the benefits of clean water. If the community could always provide itself, free of charge, with unlimited amounts of clean water, the use of the stream by the polluters would not be an issue. However, the fact is that there is always a value attached to enjoying clean water.

Accordingly, water resources should no longer be considered as free, and their scarce services should be optimally allocated among different users in order to maintain the quality of the environment.

Economic theory states that the market system, when functioning properly, can solve the problem of scarcity by allocating resources in an efficient way through price mechanism (Stigler, 1960). The market system, however, could fail in its function for many reasons. The phenomenon of market failure is particularly pertinent to the environmental resources due to the nature of these resources as "public goods". To overcome this failure a measure of public intervention has been suggested. There are many different forms of intervention, one of which is the effluent charge strategy.

The objective of this chapter is two-fold. First, to present the idea of the market system and to discuss the reasons that have led to market failure in water resources planning; second, to evaluate various forms of public intervention, emphasizing the effluent charge strategy.

3.2 Market System and Resource Allocation

According to the theory of welfare economics, a resource is optimally allocated among all users when the welfare of society would decrease more by taking a unit of resource away from one user than it would gain by giving it to some other (Mishan, 1967). The value to society of employing the last unit of a resource in a certain way (i.e., marginal social value) is usually taken as the price. Therefore, if the output of all goods and services was pushed to the point where the benefit loss to society of producing the last unit (marginal social cost) was just equal to its price (marginal social value), resources would be optimally distributed among different uses and the pattern of output would have maximum value to society.

Analogously, the resource is optimally allocated among different uses when the marginal cost of producing the last unit of goods (i.e., marginal private cost) equals its price. Therefore, when the marginal social cost equals the marginal private cost, and they both equal the unit price of the resource, then the resource will be optimally allocated.

Price in this sense reflects the relative importance of goods and resources in different uses. Usually, prices are determined in a free market through the forces of supply and demand. The perfect market should provide decision makers (producers and consumers) with information (in the form of prices) covering the relative profits and costs of using the resources at hand in different ways. Where all goods and resources pass through free market, and where there is perfect knowledge and resource mobility, prices serve to guide resources to their most beneficial use.

If there is no market, however, for some valuable resources, or if the market does not function properly, the resulting resource allocation will not be optimal. In this case, it is said that market failure has occurred.

The phenomenon of market failure is particularly pertinent to the environmental resources for three main reasons. First, there is lack of property rights. For the market to function properly, the ownership of the resource must be clearly definable and enforceable so that the owner can prevent others from using, benefiting from, or damaging his resource. Since environmental ownership is not established, polluters do not have to either pay the owner for using it or compensate him for the damages caused.

The second reason relates to the "public goods" nature of the environmental resources. Public goods, once supplied to an individual, are by their very nature freely available to all; it is not practical to exclude some people from using them. Since other users cannot be excluded because of non-payment, producers of public goods are unable to collect revenues from beneficiaries. This situation could induce the producers to provide such goods in less-than-optimal amounts*. Clean water and air are typical examples of public goods. Suppose a single firm is granted exclusive property rights to waterways in a region. The firm has the right to sell clean water (that is, water reduced in pollution) to buyers willing to pay. But if pollution is reduced for one user, it will be reduced for all the users in the region, whether or not they have to pay. Since the firm cannot collect from all beneficiaries the total cost of the clean water, it will have little or no incentive to curtail pollution.

The third reason for the failure of the market system to reach an optimal pattern of resource allocation has to do with the externality effects.

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* The optimal quantity of a good is that amount at which marginal value (social cost) equals marginal cost (private cost). In a case where the marginal value of a good is greater than the marginal cost, production of goods should be expanded as long as there is an opportunity to capture such gain. But where a characteristic of the good is its public nature, the producer may not be able to capture the full marginal value and hence lacks the incentive to expand output to the optimal level.

There is a class of economic activities characterized by what is called "externalities", of which pollution output is a prime example. In these activities, optimal output does not result through market function because some of the costs generated by these activities are not borne by those responsible for them. Externalities in using water resources, for example, can occur when upstream users discharge their waste into the stream at no cost to themselves, inflicting damage and costs on downstream users. These costs will not normally enter into the calculations or accounts of the upstream users; they are "external" to such calculations. At the same time, downstream users have no power to ask upstream users for compensation.

The externality effects of water pollution will result in the misallocation of water resources as well as the production of socially undesirable patterns of output. In the absence of any obligation to properly dispose of their wastes, polluters will be encouraged to enhance the amount of their production, which is artificially cheap. This tends to induce the over-production and over-consumption of some products which may have the socially undesirable result of under production and under consumption of other products.

Kneese & Schultze (1975) brought attention to the fact that a society that allows waste dischargers to neglect the compensation costs of their waste disposal, is encouraging them to produce too much waste without any concern for social needs. This results in a misallocation of water resource services and a considerable deterioration of water quality.

3.3 Economic Incentives For Water Pollution Control

As discussed before, water resources are broadly regarded as public goods. Managing these resources, therefore, is largely a matter of applying the general principles of public goods management. This is achieved through public intervention in order to account for externalities (Kneese, 1964). The public authority responsible for this intervention is required, at first, to establish an acceptable policy regarding water quality standards. These standards are not rigid, and they can be changed according to any circumstances. Once the quality standards are established, the public authority need only seek the best method of implementing the policy. Although a number of methods have been suggested over the years, the following three have received the most attention, both theoretical and practical:

i) Regulation Enforcement Strategy - This is the most widely used control strategy, and it can be viewed as a two-step process. First, the authority establishes allowable quantities and compositions of discharges for each polluter, as well as the time and place of discharge. Second, the authority legally enforces such regulations, i.e., it can impose sanctions when violations are detected.

The strategy could succeed in optimally determining the amount of waste discharge at each pollution source, provided that the public authority has all the information regarding the time of discharge, the amount of waste, the type of waste treatment technology used, the treatment cost, etc., for every polluter in the region (Dales, 1968; Freeman and Haveman, 1972).

ii) Subsidies Strategy - The public authority may decide to subsidize municipalities or industries on a portion of their expenditures on pollution treatment so as to keep the amount of waste down to the level that it has established (Dales, 1968). The subsidy may take different forms, such as payments for building municipal treatment plants and allowing industries to divert their wastes to these plants at costs below normal, or giving firms grants and loans to set up their own pollution control facilities (Dales, 1968). The subsidy may also be offered in the form of a bonus of a certain number of dollars per unit of treatment achieved. For example, a certain sum may be offered for each percentage reduction of BOD level in a river. In such a case, assuming that the authority has set the tolerable pollution limit, by one way or another, at a certain level "$\overset{*}{Q}$", the subsidy should be set equal to the marginal benefit of the unit increase associated with a unit decrease in pollution at the "$\overset{*}{Q}$" level. The polluter therefore will have an incentive to increase treatment up to the "$\overset{*}{Q}$" level as long as his marginal cost is less than the per unit subsidy, but not beyond that level.

(iii) Effluent Charge Strategy - This strategy requires that anyone discharging waste into a waterway has to pay the public authority a certain sum (effluent charge) per unit of discharged waste. The method was originally suggested by Kneese (1964), then developed and rationalized by many others such as Dales (1968), Baumal and Oates (1971) and Tietenberg (1973 (a),(b)). The method proposes to bring the limited assimilative capacities of watercourses under the effect of the market function by charging those who would use these common resources a certain price. Each user is led to compare the cost of using the resources for discharging waste with the cost of handling his waste disposal problem in some other ways. His only guide is the relative cost of alternative procedures, one of which is discharging the waste into the environment untreated, and paying the charge.

This method provides incentive for the efficient use of the environment, similar to the incentives which induce efficiency in the use of labour, capital, and land (Freeman, 1971). The waste dischargers will realize the cost of degrading the environment through paying effluent charges. This could bring the firm's private costs (including the charges) into equality with the social costs, resulting in an optimal pattern of water resources allocation.

3.4 Evaluation of Effluent Charges Strategy

Choosing appropriately among the above three strategies is not a straightforward task, since the pollution problem itself has many socio-economic effects on such things as industrial location preferences, income distributions, desired production patterns, population distribution, and standards of living (Solow, 1971). Kneese and Schultze (1975), however, have mentioned three criteria that should at least be met for the chosen strategy to be successful; the strategy should be: (i) effective enough to cope with the complex relationships of the pollution problem (ii) flexible enough to achieve the social need of pollution reduction, and (iii) efficient enough to achieve the least costly means of pollution reduction.

Apparently, the regulation enforcement strategy, which is the most widely used method, has failed to achieve the required reduction at reasonable cost to society. A study issued by the Environmental Conservation Agency of Vermont (1972) gave two reasons for this failure. First is the little attention that has been given, in all legislations concerning water quality management, to the issue of economic incentives. Second is the neglect of the economic value of the waste assimilative capacity of watercourses. Since the early 1970's there has been a growing interest in investigating alternative policies. The effluent charges was one of these alternatives that has received great attention and interest from environmentalists, and from most economists as well. This interest apparently stems from the common view that establishing a price for the water resources would work as an economic incentive to correct and adjust the malpractices of dischargers. The strategy, however, is facing some criticisms and misconceptions. In what follows, the effluent charges strategy is critically evaluated in the light of the above three criteria.

Effectiveness - It is most likely that a monetary incentive will be more effective for reducing water pollution than any legal penalty. The monetary incentives are the essence of the effluent charge strategy. The regulation-enforcement strategy, however, does not provide such incentives; rather, it enforces the regulation through legal penalties which are difficult to administer because of the problems involved in detecting violations (Freeman, 1971). On the other hand, under ideal conditions the regulations could provide enough incentives for the dischargers to just meet the standards, while in the effluent charges strategy, the dischargers would have a continuing incentive to devote research and engineering talent to finding less costly ways of achieving further reductions from the standard requirements, since a charge must be paid for every unit of pollution released.

As for the effectiveness of the subsidies strategy it could generate results entirely opposite to those it is expected to achieve. For example, a large waste-producing industry may be able to reduce its waste at a cost per ton that is less than the subsidy it earns per ton by doing so. The industry may expand its production in order to engage in the profitable business of producing waste and then treating it.

Flexibility - Since the techniques and costs of removing pollution vary widely from case to case, control policies that emphasize one particular appraoch, or impose specific limitations on all polluters are bound to be rigid, and to result in inefficiency (Kneese and Schultze, 1975). The effluent charges strategy seems to offer the greatest flexibility, in the sense that it does not specify how to deal with pollution; the choice is left to the dischargers who have a wide range of options. They may be able to undertake treatment of part or all of the residuals, they may change the process to reduce residuals per unit of output, or they may find that recycling and material recovery is less expensive than either treating the waste or paying the charge. In any case the dischargers are led to compare the cost of handling their waste disposal problem with the cost of using the river as a waste receptor. The strategy, moreover, does not need detailed and accurate information, especially regarding the treatment cost for every discharger in the region (Freeman & Haveman, 1972). It is sufficient to start with a little information; then, once charge value is known each polluter makes his own cost calculations and responds to the public authority by reporting the amount of pollution he will discharge. Using this information, the authority can calculate a new schedule of effluent charges. The procedure continues in this way until it forms an optimum schedule of charges for the attainment of the given quality standards.

On the contrary, in the case of the regulation-enforcement and subsidies strategies, detailed information about the treatment costs and discharge points must be available to the authorities (Baumol & Oates, 1971). These represent a massive administrative problem, and it would be difficult and expensive to collect such information.

Efficiency - Due to the flexibility of the effluent charge strategy's management of pollution control, dischargers, are more likely to seek efficient and least costly methods of pollution reduction. An efficient method requires that different firms reduce pollution by different amounts, depending on the cost of reduction. Moreover, each firm - in addition to applying conventional waste treatment techniques - should take advantage of a wide range of control alternatives: modifying its production processes, recycling its byproduct wastes, and using the varieties of its products which cause less pollution. Efficiency, in this sense, is more inherent in the effluent charges strategy than in the other two.

In spite of the clear advantages of the effluent charges approach, the strategy has been misunderstood and criticized by various groups of environmentalists, businessmen, and economists. It is important, in the course of evaluation of the strategy, to put the more substantive of these criticisms into proper perspective, and to correct any misconceptions:

The main criticism, raised by some environmental groups, is that the strategy is an open invitation for the polluter to purchase the right to degrade the environment. It is important, in evaluating this argument, to recognize the natural capacity of watercourses to assimilate waste loads. It would be unreasonable to neglect the economic value of the waste assimilative service. The effluent charge strategy, like any other economic strategy, makes proper allowances for this within the limits of water quality established by the authorities. The argument, however, could make sense if the required payment of the charge fails to maintain the desired quality limits or to induce dischargers to search for new treatment methods in order to reduce liability to the charge. Nevertheless, these situations can be managed if the charge is set above the costs of the highest treatment level, in order to induce the profit-maximizing firms to search for cheaper methods to reduce their pollution, at least to the specified limits (Kneese & Schultze, 1975).

Another criticism has been advanced by business groups, who argue that the effluent charges would hinder industries' ability to reduce pollution and finance pollution control equipment. They maintain that firms will find it more expensive to reduce pollution by a given amount, because in addition to the real cost of waste treatment they will also have to pay the effluent charge on their residual wastes. By contrast, it is argued that if they were obliged to reduce pollution by direct regulation, for example, they would incur only the real cost of the treatment.

In order to counter the above criticisms, one might put forward two economically-based arguments in favour of the original proposition. First, in the ideal situation, authorities would choose the method which will be cheapest for the economy as a whole, not for the firms only. Beckerman (1975) has argued that, on the national economic scale, the only real cost of pollution treatment is the cost of real resources used by the firms to reduce pollution, that is, the cost of labor and raw materials employed in the treatment processes. Efluent charges, or the effects of the charges, must be excluded in calculating the actual treatment costs, since the charges are considered as transfer payments rather than resource costs. It is assumed that the collected charges must be transferred to other public expenditures or be offset by reduction in other governmental tax revenues. Therefore, the only real cost of pollution control is the total cost of the resources used by the firms.

Second, the proposition of the business groups suggests that the main effect of any decrease in profits would be to reduce expenditures for the treatment of residues. without appropriate incentives, however, it is probable that businesses do give low priority to investment in pollution control. It is the purpose of the effluent charge strategy to alter these priorities and to put more pressure on firms to seek efficient methods of pollution treatment.

The third criticism came from some economists, primarily from Coase (1960). Coase argued that any form of taxation such as effluent charges is likely to lead to a misallocation of resources. He argued that private negotiation between the two parties may work as an optimum method. There are, however, three main barriers which prevent greater reliance on this approach. First is the size of the environmental units in which property rights must be vested. A major river system, for example, is inherently indivisible. To secure the economic benefits, based on creation of property rights, control over the whole system must be granted to a single entity (Freeman III, 1971). Yet Coase's approach would require the establishment of a large number of entities to own the system, a case which is quite difficult to arrange.

The second barrier is the presence of public good attributes, in many environmental services, which could not exclude users who have not paid for the services provided.

The third barrier is the cost associated with the bargaining processes. The processes are costly in the sense that it takes time to gather information, evaluate other alternatives, and execute the transaction. Because many parties are involved in the environmental negotiations, this cost tends to be high. Freeman (1971) realized that the cost of government action for administration and enforcement of effluent charge strategy is smaller in comparison to the private transaction costs when the bargaining processes are taking place.

In conclusion, the effluent charge strategy seems to be promising as an economic instrument for controlling water pollution. This stand relies on three main considerations. First, imposition of effluent charges encourages a pattern of waste management among different firms and municipalities that tends to minimize the cost of control for the river system as a whole. Second, the charges provide a continuing incentive to adopt improved technology as it becomes available. Third, this strategy is much more likely to be enforceable than the other alternatives.

CHAPTER IV

EVOLUTION OF EFFLUENT CHARGE STRATEGY - A LITERATURE SURVEY

4.1 Introduction

Early in the 1960's, research began on the conceptual design of, and rationalization for effluent charges as a strategy for pollution control. Unfortunately, the research progress in this area has been relatively slow. The strategy, at that time, faced opposition and misunderstanding from different industrial, political, and environmental groups. However, the growing awareness, in the early 1970's, of the failure of present control strategies to cope effectively with the pollution problem, has contributed significantly to the willingness of examining other alternatives, particularly the effluent charge strategy.

During the last few years there has been some work to develop both the theoretical basis of effluent charges, and to pave the road toward their practical application. These efforts have successfully produced two theories for establishing charging methods by means of the market system. Yet, little has been done to put these methods into practice.

This chapter presents first, a survey of the works which have been carried out to date on the development of the theory of effluent charges; second, a summary of the studies which have used the strategy within a framework of a water quality management model.

4.2 Theoretical Development of Effluent Charge Strategy

The theoretical foundations of the strategy have been set forth by Kneese (1964). He suggested that a uniform charge rate be levied against all the polluters in a region equal to the dollar value of the marginal damage caused by waste discharge. Kneese realized that a charge equal to the marginal pollution damages will lead to efficient allocation of the water resources. People discharging waste will try to minimize their own costs by equating their marginal costs of waste reduction with the effluent charge.

At that time, the main difficulty with Kneese's proposal lay in obtaining a reasonable estimate of the monetary value of the marginal damage cost of pollution. This difficulty was due to the fact that the number of activities involved and the number of persons affected by the damage were so large that it would be difficult to collect adequate information regarding the damage cost with a reasonable degree of accuracy. In addition, the intangible nature of many of the consequences - damage to health, and the aesthetic costs - added to these difficulties. However, later on Kneese & Bower (1968) reported some promising work constituting a first step towards a monetary estimation of the pollution damages. But the study included the costs due to the loss in recreational benefits only.

To overcome the difficulty entailed in Kneese's proposition, two variant methods for determining the appropriate charge level have been devised. In the first method, Dales (1968) suggested that the government can control the demand on water resources when it is used as a waste receptor. According to Dales the government then issues a number of "pollution Rights", each Right giving whoever buys it, the right to discharge one equivalent ton of waste into the river. The Right holder can also sell this Right or buy it from any other Right holder. Because transferable and full property rights always command an explicit price, the establishment of such Rights makes it easy to establish a free market for them. In turn, the buying and selling of Rights in an open market results, theoretically, in an efficient allocation of the water resources among different users. On the other hand, as time goes on, we could expect the growth of population and industry to result in an increase in the demand for Rights. Since the number of Rights issued cannot be increased, the price of the Rights will move upward, thereby stimulating the incentive of waste dischargers to treat or reduce their waste in order to decrease the number of Rights they must purchase.

In the second method, Baumol and Oates (1971) argued that the call for imposing a charge on polluters equal to the marginal damage costs has rarely proved feasible. They suggested, instead, that the government could establish, at first, a set of somewhat arbitrary standards of environmental quality levels. Then they could impose a set of uniform charge rates on waste emissions rather than attempt to base them on the unknown values of marginal damage. They recommended that the charge should be high enough to attain the environmental quality standards. The appropriate charge rates that yield the desirable level of pollution control at total minimum cost, can be reached by the process of trial and error. If after the first trial, the level of pollution is found to be higher than the desired level, the charge rates can be increased to force dischargers to reduce their pollution level, and vice versa. This method is known as "The Pricing and Standard System".

Since the effluent charge strategy has been set up, some decision and law makers, especially the economists, have expressed their acknowledgement of the strategy. Many papers have been published to clarify the rationality of using it, to defend its theoretical and practical basis, and to explain the merits of the strategy. Boyd (1971) supported the strategy on the basis that the charges collected would be used to reimburse the public authorities for the cost of constructing and operating dams, aeration devices, etc., in order to expand the waste-receiving capacity of the river. At the same time the water quality requirement would be attained. Solow (1971) appreciated the strategy for three main reasons. First, the fact that the strategy attains the desired abatement level of pollution; second, that it provides enought incentive for the polluters to search for cheaper methods of waste abatement; and finally, the authorities need little information regarding the quantity, cost, and timing of pollution.

Freeman & Haveman (1972), in their defence against the strategy, made a comparison between Regulation Enforcement and effluent charge strategies. The comparison was based on the effects of each strategy with respect to factors of: inflation, resource misallocation in the presence of monolopy, administrative problems, hindering of industrial abatement, and the cost of attaining environmental quality levels. They concluded that the effluent charges is far more advantageous than the other strategy with respect to the above factors.

Ruff (1970) in his comparison between pollution Rights and The Pricing and the Standard System noted that the two methods will lead to the same results, as long as the authorities succeed in establishing correctly either the amount of pollution Rights, or the starting charge level. Tietenberg (1973,a), on the other hand, realized that the Pricing and Standards System is easier and least costly to administer than the pollution Right method.

Tietenberg, however, disagreed with the notion of proposing a uniform charge rate for all the polluters in the region. To demonsrate this, he employed an abstract model for controlling pollution, using effluent charges as a basis for addressing the issue of whether or not the pricing and standard system is a sufficient means for a government to efficiently allocate environmental resources, assuming that consumers, producers, and the government are acting non-cooperatively in their own self interest. The model described the relationship of pollution with consumers through their utility functions, with producers through the production functions, and with society through a social welfare function. The analysis showed that the superiority of this control system depended on imposing a set of non-uniform charge rates on the polluters in order to attain the minimum cost advantage. The charge rates should differ according to geographic, temporal and spatial factors. Similar conclusions have been reached by Ackerman (1973), who concluded that the charge rates should be based on the effect of an emission on the community, and not necessarily on the amount generated.

Baumol & Oates agreed with Tietenberg's proposition in their recent work (1975) which dealt with different economic policies for environmental resources control. Brumm and Dick (1976) also concluded that, from a practical standpoint, the Pricing and Standard System has considerable appeal in terms of overcoming the problem of lack of information regarding the treatment cost functions in order to set up optimal charge rates. Orr (1976) realized that the greatest advantage of the effluent charges was in their provision of decentralized incentives for technological change in wastewater treatment methods. Magat (1978) also appraised the effect, in a dynamic world, of the effluent charges and regulation - enforcement strategies on both the rate and the direction of technical advance for effluent abatement technology and output technology. The results demonstrated that, under certain conditions (easy labor substitutability), constant effluent charge induced the firm to allocate effective research and development efforts to effluent abatement technology. On the other hand, using constant standard policy induced the firm to allocate more efforts to the output production technology.

In addition to technical advance, the constant level of effluent charge was found to fail in limiting the increases in the effluent discharge rates. In other words, for a typical polluting firm, a rising charge rate is needed to halt growth in the effluent level with advancing technology. Regarding this result, Magat realized that, in order to reach a given goal for environmental quality, the iterative process suggested by Baumol & Oates (1971) would never converge to a fixed charge level. Magat therefore suggested that, in order to maintain the environmental quality goal, government would have to either inform polluters that the initial charge level would rise over time at some unspecified rate, or initially announce a rising charge function. The author, however, is in favor of the former approach.

4.3 Practical Application of Effluent Charges

In the realm of practical applications of the strategy, the study given by Johnson (1967) is considered to be one of the pioneer studies in this respect. The study aimed, in general, at gaining some practical experience in the estimation of effluent charge levels in the Delaware Estuary. It was found that the cost of waste treatment, induced by a charge level, will approach the least costly treatment plan. The study concluded that effluent charges should be seriously considered as a method of attaining water quality management. The study, however, simply formulated the computational model as a linear one.

Upton (1968) presented a linear model of water quality management in order to find the optimal amounts of waste discharge that minimized the total treatment cost incurred by all the polluters and the cost of low flow augmentation, such that the water quality levels should be maintained. The control of waste load discharges by the charging method has been shown to be preferable to the regulation control method under some conditions. The study showed that an optimal set of charges existed which would induce the polluters to discharge optimal amounts of waste.

Hass (1970) suggested a decentralized, decision-making scheme, for obtaining the optimal treatment configuration for meeting water quality standards along a river basin, simultaneously determining optimal pollution taxes to achieve this configuration. It was assumed that the authority knew the quality standards desired and the cost of low flow augmentation, and that polluters knew the individual treatment cost functions. The problem confronted by the authority was to find the combination of each polluter's treatment plans and the level of flow augmentation, which minimizes the cost of achieving the standard imposed upon the river at the end of each reach. The authority wished to have each polluter treat waste to the point at which the marginal cost to society of disposing waste was equal to the marginal cost to the polluter. Hass formulated the objective function and constraints of his problem in the form of a linear programming problem.

The implications of Hass' study is that authority can, through a planning process involving proposed charge rates and polluter responses, determine a set of near-optimal pollution charges without complete knowledge of treatment cost functions. Disregarding the linearity assumptions in Hass' model, there is no guarantee that the solution is optimal since the polluters have no incentive to be honest in their responses. In fact, it is in their interest to understate their discharges to lower the resulting effluent charges.

In 1972, Agency of Environmental Conservation in the State of Vermont conducted a comprehensive study regarding various methods of establishing effluent charges and the feasibility of their application. Six methods were reported: (1) charges based upon the monetary estimate of the magnitude of pollution damages, (2) a uniform charge to all polluters, (3) uniform charge rate weighted by stream classification or zone, (4) a charge rate based on dilution factors or population equivalents (a composite index derived from the concentrations of several residual pollutants), (5) charges based upon annual cost of treatment, and finally, (6) charges based upon stream quality degradation.

Each of these methods was evaluated according to six criteria: (1) Efficiency of resource allocation, (2) Relation of charges to instream economic damages, (3) Equity, i.e., whether an effluent charge system would result in any impairment of existing "rights" or "privileges" without some form of compensation, (4) Incentive effects on dischargers, (5) Administrative and technical feasibility and (6) Income potential generated by effluent charges.

The main purpose of the study was to discuss the problems of selecting and implementing the best method, among the six alternatives, which would suit the state of Vermont's water pollution control objectives. In view of the above assessment, the charge method based on discharger's annualized cost of treatment was found to be the most appropriate to the pattern of water quality management set by the state.

Elliot & Seagraves (1972) studied the impact of surcharges on industrial waste, using a sample of 198 observations from 34 cities. The study showed a substantial impact following the imposition of a moderate waste charge. It was indicated that a 45% reduction in waste load would follow from the imposition of a modest surcharge of 2.7¢/lb. of BOD.

Taylor (1973) presented a model for planning an efficient water quality program within a river basin. The control method, called "rent allotment control", combined the effluent charge with the waste allotment or "Pollution Right" suggested by Dales (1968). It was implemented through a bargaining process between the authority and the waste dischargers that may be characterized as an "N-person prisoner's dilemma". The polluter was asked to respond with an allotment to which he would be willing to adhere and with which he would be willing to pay the effluent charge at the end of a prescribed planning period. If the noted charge was levied, violations of this agreed allotment would not be permitted. Furthermore, the polluter was told, if the allotment response was not low enough, although no indication was given of what "low enough" meant, the effluent charge would be raised and a new request for bids sent out.

The bargaining process, therefore, provides the authority with information about individual waste treatment costs, and terminates in a set of agreements on rents and allotments which depend upon the bidding strategies adopted by each polluter. Through successive iterations of bidding for waste allotment, the authority would reach an optimal situation where each polluter bids for an allotment such that the marginal cost of additional withheld waste is equal to the effluent charge. In fact, the main merit of this method is that it would overcome the dishonest reporting of information by some polluters. The method, however, might fail when all the N polluters collude and underbid for the allotment.

Ferrar (1973) realized that it was not consistent to establish a static effluent charge rate to account for a situation of dynamic demand on water resources as a waste receptor. He therefore suggested a non-linear, progressive effluent charge scheme to account for the dynamic phenomenon of growing demand in a region. To establish his effluent charge scheme for meeting a specified level of regional environmental quality, he applied the "internal point penalty function" method, suggested by Fiacco & McCormick (1968), such that at any time the polluter will pay a charge directly proportional to the rate of increase in his demand. The scheme, however, requires a public authority to request from polluters the total and marginal costs of present treatment activity. Therefore, such an approach could fail to deal adequately with the problem caused by firms supplying misleading information, particularly cost information, to the public authority.

O'Sullivan (1974), in his survey of the measures taken by common market countries to curb discharge of industrial effluents to waterways, stated that the basis of charging for both community and industrial discharges is the pollution equivalent (P.E.) oxygen demand. This is a measure of the average daily discharge of oxygen-demand substances per head of population. The charge per P.E. of pollution discharge varies according to the area of the country, the total load burden of the receiving water, and whether the discharge enters large or small rivers. In general, the charge, as O'Sullivan mentioned, varies from $2.00 per P.E. to about $7.00. However, the charge scheme of toxic wastes has not been developed yet.

The study given by Wenders (1975) analyzed the impact of improvement in pollution abatement technology on the cost of a firm working under three alternative methods of pollution control. The methods were: effluent charge, subsidy, and regulation-enforcement strategy. It was shown that the cost reduction would be greatest if the firm was operating under the effluent charge strategy. In addition, the incentive to improve pollution abatement technology would be greater if effluent charges were used to control pollution.

However, Nielson and Hwang (1975) reached a different conclusion when they studied the interaction between the incentives offered by the charge, and the individual polluters choice of waste water treatment technology. They concluded that increasing the charge might both fail to improve environmental quality, and increase production costs.

Marin (1978), in his search for the best control method of pollution, concluded that effluent charges seemed to be suitable for controlling river pollution more than air pollution (controlling sulphur dioxide) due to the advantages of: governing the number of polluters involved, monitoring pollution emissions, and the existence, somehow of a relationship between inputs and emissions.

Oates and Strassmann (1978) realized that the compelling case for the use of effluent charges to control polluting activities, as it seems to most of the researchers, proceeds from the assumption of profit maximizing behaviour by polluters. Since profit maximization is not presumably the primary objective of public organization, Oates and Strassmann studied the effectiveness ofusing the effluent charges to control the public sector sources of pollution. He employed the Niskanen model of bureaucratic behaviour (Niskanen, 1971) to investigate this issue. The Niskanen model operates on two basic premises: first, when the objective of the bureaucrat is to maximize the size of his budget, in order to serve as a proxy variable for the prestige, power, prerequisites, etc. of the bureau. This indicates the presence of "fat" in the bureau's budget, and the bureau is said to be demand constrained; second, when the bureaucrat works under shortage, i.e., the cost of providing output exceeds the bureau's budget. The objective of the bureaucrat is cost minimization, and the bureau is said to be budget constrained.

The study considered the two cases. It was found that the effluent charges can induce significant reduction in pollution activities when the bureau is budget constrained. This is because where there exists a less polluting technology such that the abatement costs are less than the effluent charges, the bureaucrat will shift to alternative technology, since the bureaucrat is a cost minimizer. The study found, however, that the response of the demand constrained bureaucrat to the effluent charges is not clear. This is because most likely the bureau can absorb the charges with some of its surplus budget with need to search for less costly methods for abatement, unless the charges are sufficiently high to push the bureau from a demand constrained to a budget constrained situation.

In fact, this study is important, since public sector sources of pollution represent a major source of waste emissions (approximately 57% of BOD accounts for the emissions coming from municipal discharges). However, more practical experimentation for the use of the charges is clearly needed.

Rinaldi, et al (1979) studied the possibility of achieving a stable and efficient taxation scheme in regional environmental management systems. Motivated by the concepts of the game theory, the scheme comprises a set of rules which, given a set of polluters, their profits and costs, and a central authority for environmental control, generates taxes to be levied on the waste emissions. The most important aspect of the scheme is its stability which refers to the possibility of overall cooperation between all the polluters. The study demonstrates that, if the damages to the environment are not negligible and if these damages must be refunded by the users of the resource, it is very unlikely that efficient and stable taxation schemes can be found if the regional authority acts as a non-profit corporation. The results also state that if the damages to the environment are neglected, or in other words, if the total benefits of the firms instead of the social benefit is maximized, the efficiency and stability are easily obtained. Increased public awareness, however, makes this solution no longer feasible. The alternative is to achieve stability and efficiency by letting the regional authority get a profit by the sale of emission rights. The higher the environmental congestion, the greater must be this profit. But if ethical or political attitudes are against this kind of solution, there is no way to maximize the social benefit without generating friction among the polluters.

CHAPTER V

DEVELOPMENT OF AN EFFLUENT CHARGE OPTIMIZATION MODEL

5.1 Introduction

The mathematical model presented in this chapter has been developed to obtain the optimal effluent charge rates to be levied against polluters using the river system as a waste receptor. The model is formulated within the framework of a water quality management system. The modified transfer equations of Streeter-Phelps (1925), as suggested by Dobbins (1964), are employed to predict the values of BOD and DO along the river. The model's assumptions, and the limitations of its applicability, are discussed first. A description of the model's structure, including the objective function and the constraints, is next exhibited. Finally, the formulation of the model is presented.

5.2 Model's Assumptions

The assumptions involved in the development of the model are as follows:

1) The model is limited to stream and river basins as main receptors of waste. The model establishes different zones along the river at points of discontinuity. A point of discontinuity arises whenever the existing conditions violate the assumptions of the transfer equations, of changes in water quality standards, or of boundaries determined by law that place a region under separate jurisdiction. Examples of discontinuity that require establishing a new zone are:

i) organic and/or thermal inputs,
ii) a change in the flow regime such as changes in stream width or depth,
iii) increase in the flow due to tributary input,
iv) changes in water quality standards as the river crosses a provincial line, (Shojalashkari, 1974).

Figure 5.1 schematically depicts such points.

The establishment of zones along the river facilitates the modelling process. Specifically, the complex nature of pollution interaction at various discharge points causes difficulty in the application of the transformation equations along the entire river if it is considered as one zone. However, by dividing the river into a number of segments or reaches, adequate results would be obtained by applying the equations, independently, to each segment.

2) Since municipal and industrial waste treatment plants are the major polluters of waterways, the model considers them as the main sources of pollution. The largest portion of waste released from these sources is degradable (Kneese, 1964); hence, the model is developed to deal mainly with this type of waste.

3) The most common measures of pollution intensity are the dissolved oxygen (DO) content of water, the biological oxygen demand (BOD), and the phosphorus concentration (PO_4). These measures are used as pollution indices in the development of the model.

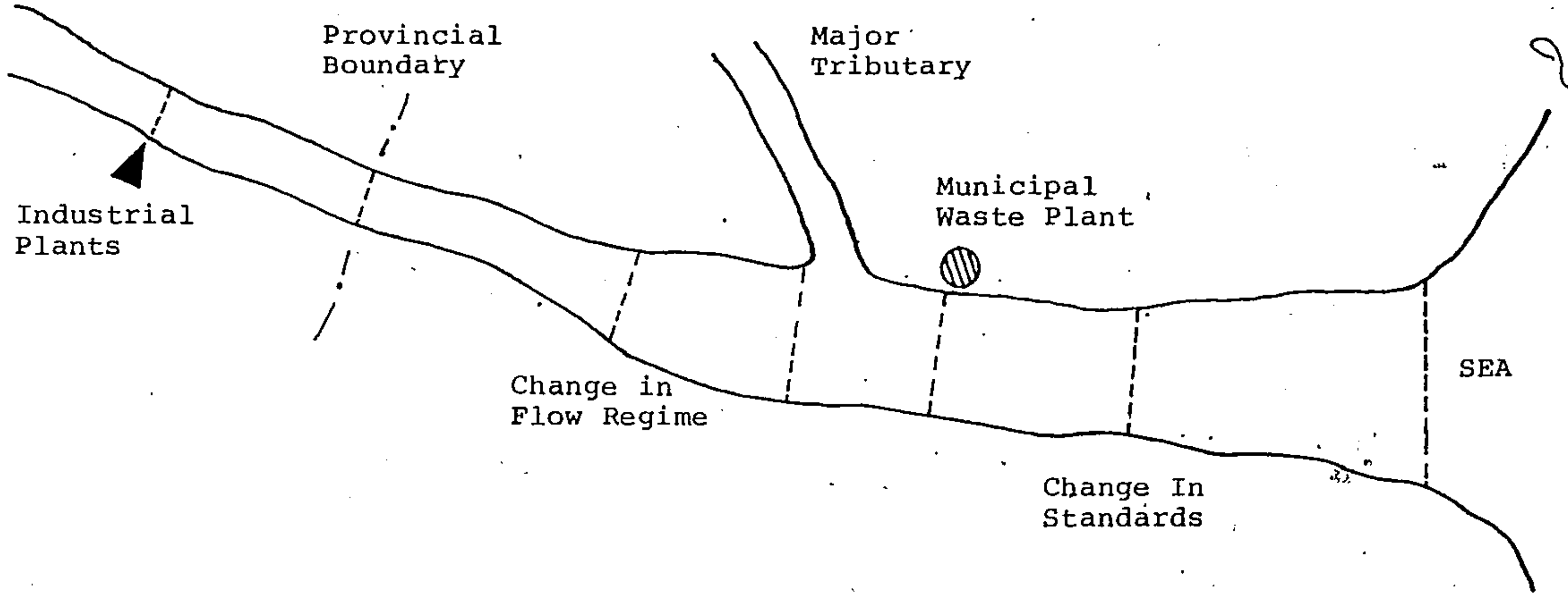

Figure 5.1 Examples of zones established at points of discontinuity in a generalized river basin.

4) The model assumes that the phosphorus has no chemical or biological interaction with the organic load and that its concentration level remains constant along the river as long as there is no change in the flow rate.

5) There are two major one-dimensional models which describe the concentrations of BOD and DO with respect to the distance from discharge source. The first is the mixed model, which predicts the BOD and DO levels along the river by assuming a complete mixing of pollutants with the water body. This mixing becomes appreciable if the stream velocity is low, as in estuaries or streams with dams. The second, or plug flow model is applicable to streams with a high flow rate and comparatively negligible mixing effects. This situation is more likely to occur in most rivers and streams, especially in upstream sections (Fan, et al, 1973).

Since the study is limited to streams and river basins, it is appropriate to employ the plug flow model, represented by a modified version of the Streeter-Phelps equations (1925), as suggested by Dobbins (1964). The modified model considers the following:

i) the sedimentation effect to remove BOD,
ii) local runoff effect to add BOD,
iii) photosynthetic action of plankton and plants to add oxygen,
iv) the respiration of plankton and plants to remove oxygen from the river.

According to the modified Streeter-Phelps equations, the BOD concentration L, and DO concentration C vary with time according to the following relationships:

$$\frac{dL}{d\tau} = -(K_1 + K_3) * L + L_a \qquad (5.1)$$

$$\frac{dC}{d\tau} = -K_1 L + K_2(C_s - C) + \langle P - R \rangle \qquad (5.2)$$

where:

τ = residence time, in days, from source of pollution

K_1 = the biological oxidation rate coefficient, day^{-1}

K_2 = the rearation rate coefficient, day^{-1}

K_3 = the sedimentation or absorption rate coefficient for BOD, day^{-1}

L_a = local BOD runoff rate, mg/ℓ/day

C_s = the saturation DO concentration, mg/ℓ

$\langle P - R \rangle$ = the rate of photosynthesis minus the rate of respiration, mg/ℓ/day.

The values of the parameters K_1, K_2, C_s, and $\langle P - R \rangle$, which are temperature-dependent, may be given as follows, (Davidson and Bradshaw, 1967):

$$K_1 = 2.35 * 10^{-7} \text{Exp}(0.0464T) \qquad (5.3)$$

$$K_2 = 0.43 * \text{Exp}(0.025(T - 273)) \qquad (5.4)$$

$$C_s = 4000.0 * \text{Exp}(-0.021T) \qquad (5.5)$$

$$\langle P - R \rangle = \frac{\pi - \alpha}{\pi(1-\alpha)} * (25 - 0.028\,(T - 303)^2) \qquad (5.6)$$

where:

α = a constant between 1 and 0

T = stream temperature in degree Kelvin

π = 3.14

6) The present study assumes that the temperature of waterways may change from zone to zone, but is constant within the same zone. This assumption is applicable in some situations. For example, when the river is long enough to flow through different climatic zones, (e.g., the river Nile in Africa where it starts at the middle of the continent, ends at far north in the Mediterranean, and passes through different climatic zones). This causes a temperature rise at some zones and a drop at some others.

7) The model considers the amount of pollutants, measured in pounds of BOD per day, as the basis for calculating the effluent charge. It seems that this method creates more incentive for dischargers to reduce the strength of their waste than if it was based on measurement of volume, for example (Maystre and Geyer, 1970).

The effluent charge, y, itself is set to be inversely proportional to the percentage BOD treatment, x, so that the dischargers are motivated to increase their treatment level and avoid the high charge. The inverse relationship may take several forms, such as:

Linear Form: $$y = \theta_1 - \theta_2 * x \qquad (5.7.1)$$

Nonlinear Form: $$y = \theta_1 * \left(\frac{1}{x} - 1\right)^{\theta_2} \qquad (5.7.2)$$

Exponential Form: $$y = \theta_1 * \exp\left(\frac{-\theta_2}{1-x}\right) \qquad (5.7.3)$$

where θ_1 and θ_2 are parameters, whose optimal values are to be determined.

The first form is simple and straightforward. The second requires an upper bound constraint to limit the charge rate from approaching infinity when x approaches zero. The third, which is used in this study is a self-bounded form, see Figure 5.2.

5.3 Development of the Model

In the development of the water quality management model, a river basin which is divided into a number of zones according to the criteria discussed before is considered. Each zone receives pollutants from different municipal and/or industrial sources, located along the river. The objective of the model is to determine the optimal values of the effluent charge rates, as well as the treatment configuration for each source, such that the desired water quality levels are maintained at a minimum total cost to all the polluters.

The objective function of the model describes the total costs which consist of the waste treatment cost incurred by all dischargers and the effluent charges paid on the untreated portion of their waste discharges. The constraints of the model represent, for each zone, the water quality constraints, and structural and non-negativity constraints for the variables involved.

In the following sections, the objective function and the constraints are developed in detail.

5.3.1 The Objective Function

The costs incurred by each polluter includes one or both of the following components: (1) the cost of cleaning

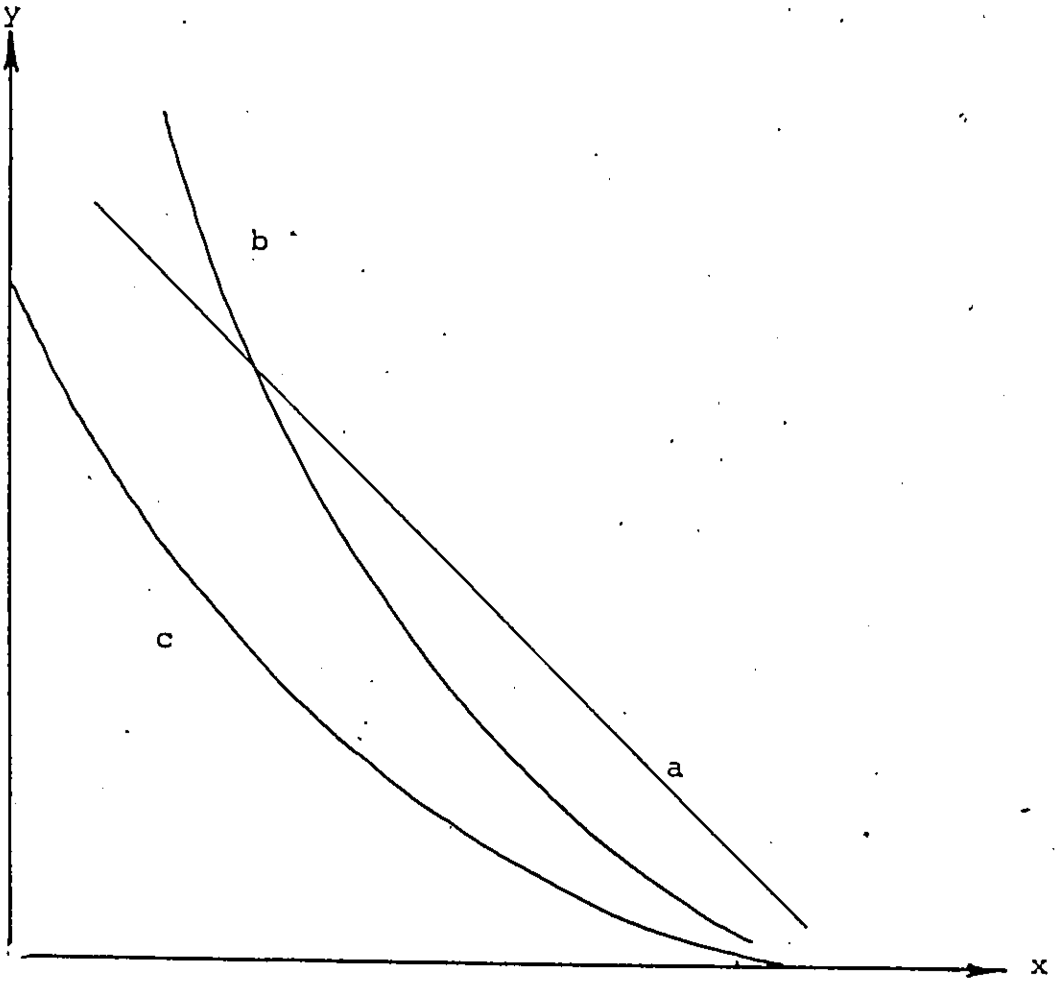

Figure 5.2 Relationship Between Effluent Charge Rate y, and Waste Treatment Level, x.

(a) Linear Relationship
(b) Nonlinear Relationship (with upper bound)
(c) Exponential Relationship (bounded).

up that portion of the waste decided to be treated, and (2) effluent charges on the remaining part of the waste that is discharged untreated. The objective function includes all such costs for the N polluters in the region.

Consider zone i, the treatment cost in this zone, FT_i, which covers only the operating and maintenance cost of the waste treatment plants, is a function of:

(i) Waste loads, measured in lb /day, of BOD, WB_i, and of phosphorus, WP_i.

(ii) Percentage treatment of BOD, x_i, and of phosphorus, z_i.

(iii) Average waste flow, $\bar{Q}_i$, measured in million gallons per day (MGD).

The effluent charge cost, FC_i, is directly related to the amount of waste load discharged, WB_i, and the effluent charge rate, y_i, which is inversely related to the treatment level of BOD, x_i.

The objective function can thus be mathematically expressed as follows:

$$\text{Minimize} \quad \sum_{i=1}^{N} \{FT_i(WB_i, WP_i, x_i, z_i, \bar{Q}_i) + FC_i(WB_i, y_i, x_i)\} \qquad (5.8)$$

5.3.2 The Constraints

The model is subject to two sets of constraints; the first accounts for the desired water quality limits, defined by the maximum concentration of BOD, the minimum concentration of DO, and the maximum concentration of phosphorus. The second set is of a structural type, accounting for the maximum and minimum limits of effluent charge rates y_i, BOD treatment level x_i, and phosphorus treatment level, z_i. The following are descriptions of these constraints.

1) Water Quality Constraints

(i) Maximum Concentration of BOD:

Assuming that LB_i is the maximum BOD content in zone i due to waste discharge, this can be represented as follows:

$$LB_i < MAXBOD_i, \quad i = 1,2,\ldots,N \tag{5.9}$$

where $MAXBOD_i$ is the maximum allowable level of BOD in zone i.

To explain how this is related to waste discharge level, the following analysis can be considered:

The amount of organic load, WB_i, of BOD in lbs/day is discharged at the beginning of zone i, causing a rise in BOD level at the discharge point, and at subsequent points downstream, as shown in Figure 5.3.

Assuming that x_i percent of the waste load is treated, then the increased amount of BOD, in mg/ℓ, at the discharge point can be calculated as:

$$\Delta L_i = \left(\frac{1.0 - x_i}{1.0}\right) * \frac{F1 * WB_i}{Q_i} \tag{5.10}$$

where:

$F1$ = a conversion factor = $0.185405 \ \frac{\text{day}\cdot\text{ft}^3\cdot\text{mg}}{\text{sec}\cdot\text{lb}\cdot\ell}$

Q_i = stream flow rate in zone i, cfs

ΔL_i = increase in BOD level at the beginning of zone i, mg/ℓ

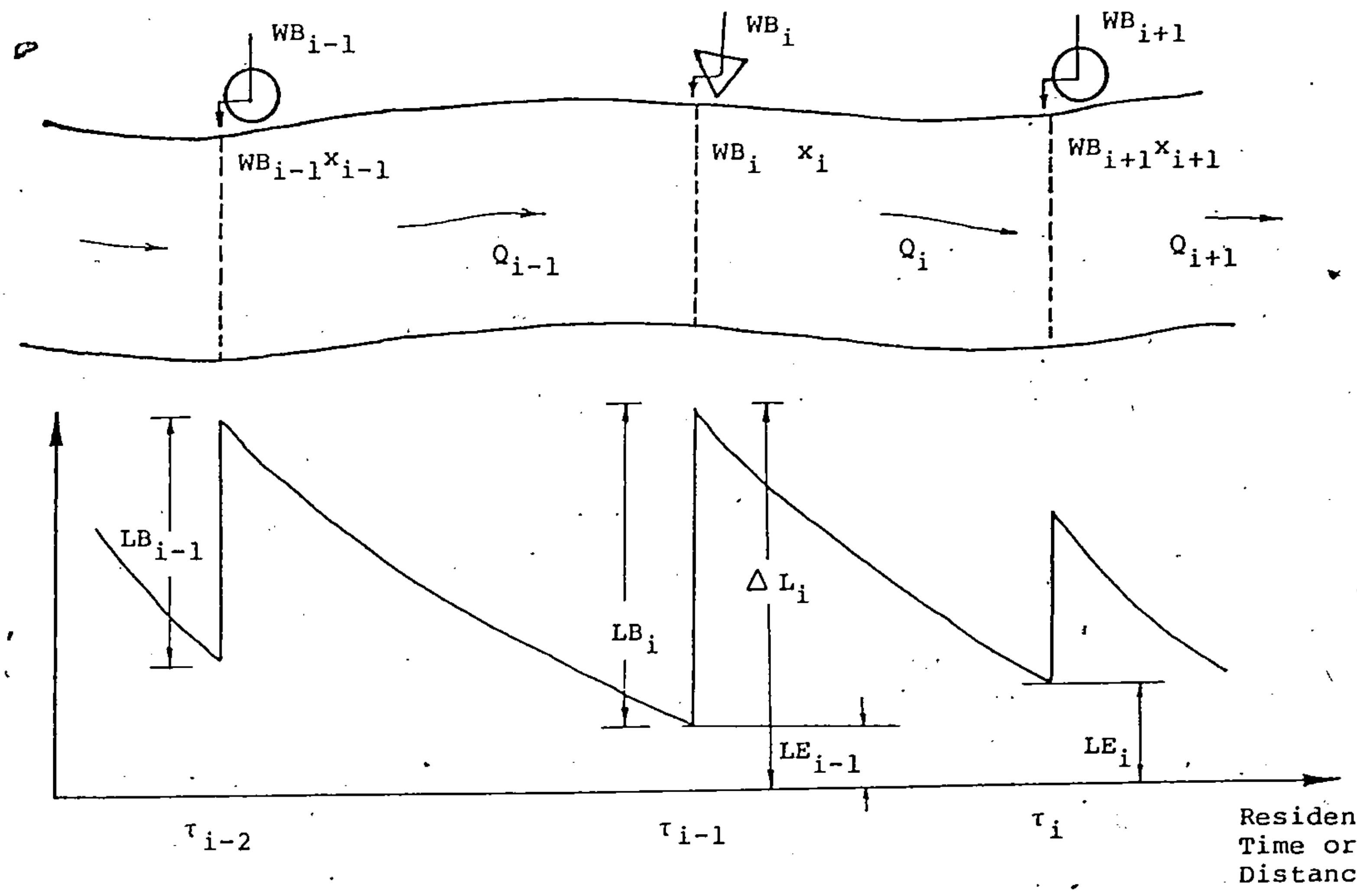

Figure 5.3 Variation of BOD concentration level within zone i.

As is shown in Figure 5.3, the maximum BOD content, LB_i, occurs at the discharge point. Therefore, we have:

$$LB_i = LE_{i-1} + \Delta L_i \qquad (5.11)$$

where:

LB_i = stream BOD content at the beginning of zone i, mg/ℓ

LE_{i-1} = stream BOD content at the end of zone i-1, mg/ℓ

For determining LE_{i-1}, note that the BOD concentration at the end of a zone is equal to the BOD content at the beginning of that zone plus the variation of the BOD along that zone. The variation of BOD can be calculated according to Equation (5.1). LE_i can be determined as follows:

$$LE_i = LB_i + \int_{\tau_{i-1}}^{\tau_i} \left[-(K_{1,i} + K_{3,i}) * LB_i + L_{a,i}\right] d\tau \; ; \quad i = 1,2,\ldots,N \qquad (5.12)$$

For the first zone, i = 1, LE_o = LU and thus:

$$LB_1 = LU + \Delta L_1 \qquad (5.13)$$

where:

LU = upstream concentration of BOD, mg/ℓ

(ii) Minimum Concentration of DO

Assuming that MDO_i is the minimum DO concentration level at zone i, the constraint states that:

$$MDO_i > MINDO_i, \quad i = 1,2,\ldots,N \qquad (5.14)$$

where $MINDO_i$ is the minimum level of DO allowed in zone i.

The minimum concentration of DO within the zone can occur anywhere within that zone, and not necessarily at the boundaries, Figure 5.4. Therefore a search process is required to locate the point corresponding to the minimum DO at each zone.

Assuming C_i as the DO concentration at the end of zone i, this is equal to the DO concentration at the end of the previous zone, C_{i-1}, plus the variations of the DO content (according to Equation (5.2)) · This can be expressed as follows:

$$C_i = C_{i-1} + \int_{\tau_{i-1}}^{\tau_i} \{-K_{1,i}\, LB_i + K_{2,i}(C_{s,i} - C_{i-1}(\tau)) + \langle P - R\rangle_i\} d\tau \qquad (5.15)$$

To determine the distribution of DO concentration in the i^{th} zone, the above expression is evaluated through numerical integration. The minimum DO concentration and its location within the zone then are determined during the course of integration, (See Appendix A). This constraint can now be formulated as:

$$MDO = \min\{C_{i-1} + \int_{\tau_{i-1}}^{\tau_i} -K_{1,i} LB_i + K_{2,i}(C_{s,i} - C_{i-1}(\tau)) + \langle P - R\rangle_i\} d\tau \quad MINDO_i, \; i=1,2,\ldots,N \qquad (5.16)$$

(iii) <u>Maximum Concentration of Phosphorus</u>

Assuming PH_i is the maximum phosphorus content at

Cs_i DO saturation level at beginning of zone i.

C_{i-1} DO concentration level at end of zone i-1.

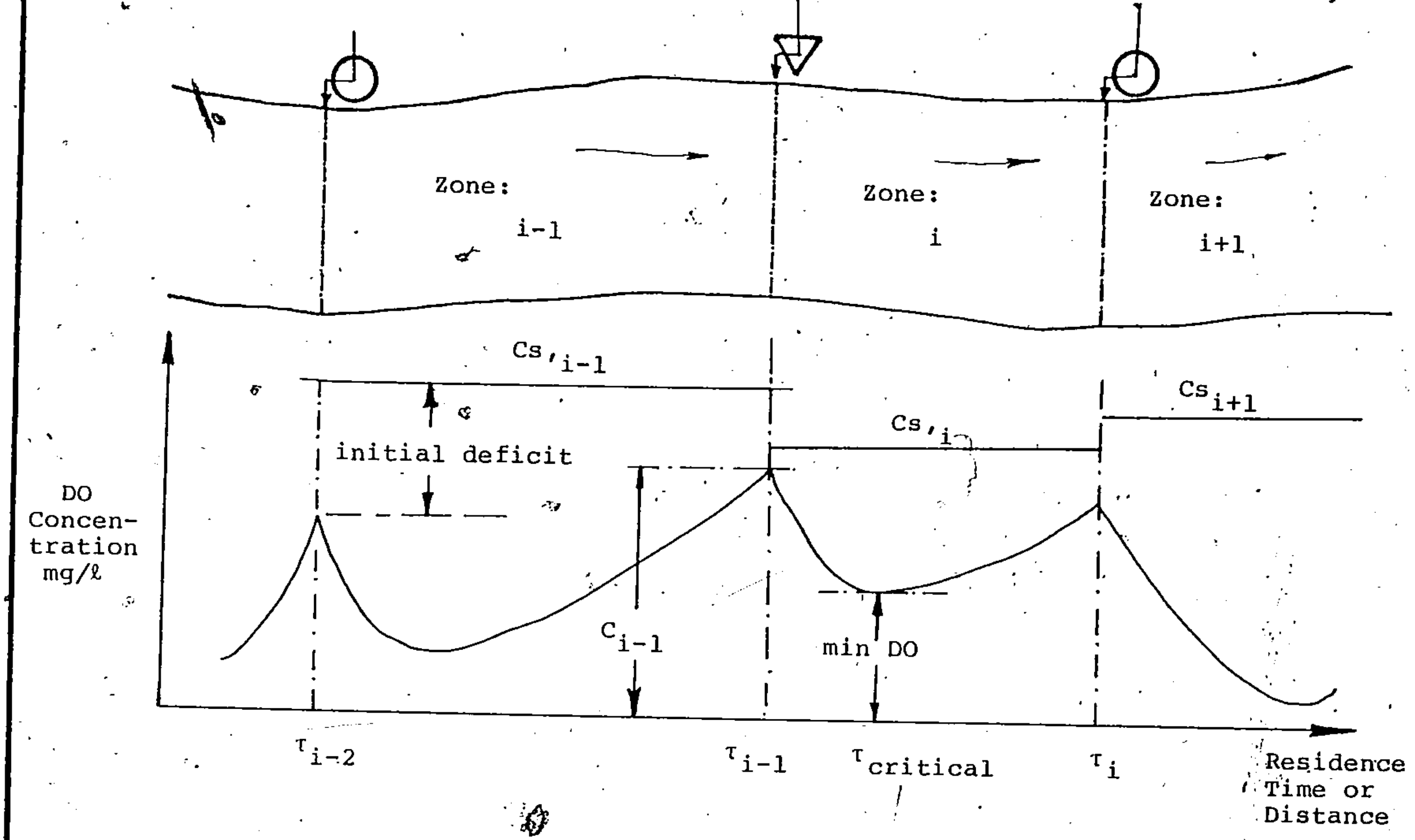

Figure 5.4 Variations of DO concentration level within zone i.

zone i due to waste discharge, this can be represented as:

$$PH_i \leq MAXPHR_i, \quad i = 1,2,\ldots,N \tag{5.17}$$

where $MAXPHR_i$ is the maximum allowable level of phosphorus in zone i.

The maximum concentration occurs at the point of discharge, and remains at a constant level throughout the zone as long as there is no change in flow rate, since the variation in phosphorus concentration level is due to dilution processes. This phenomenon is shown in Figure 5.5.

The maximum concentration level at the discharge point can be calculated as follows: Assume the produced amount of phosphorus waste load is WP_i in lbs/day. If z_i percent is the treatment level to reduce the phosphorus pollutant level in the influents, then the phosphorus concentration, EP_i, in the effluents, measured in mg/ℓ, can be given as:

$$EP_i = \left(\frac{1.0-z_i}{1.0}\right) * \frac{F1*WP_i}{Qe_i} \tag{5.18}$$

where:

Qe_i = the effluent rate, cfs

$F1$ = the conversion factor, $\frac{day \cdot ft^3 \cdot mg}{sec \cdot lb \cdot \ell}$

If it is assumed that the flow of the stream at the end of zone i-1 has a phosphorus concentration level PH_{i-1}, in mg/ℓ, due to the accumulated waste effluent discharged at previous zones, then the total phosphorus concentration

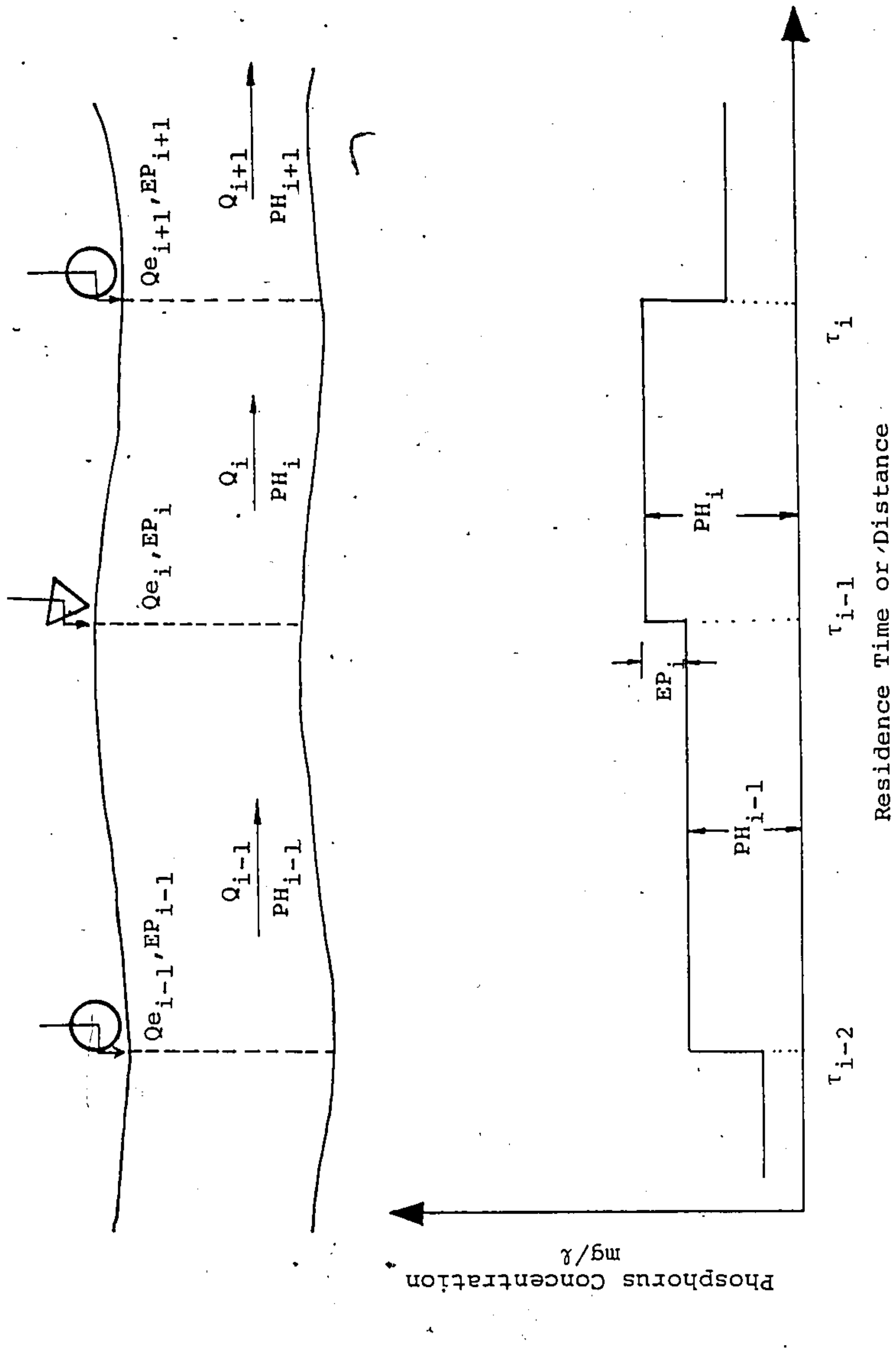

Figure 5.5 Variation of Phosphorus Concentration with Zone i.

PH_i, in mg/ℓ, at the beginning of zone i would be:

$$PH_i = \frac{EP_i \cdot Qe_i + Q_{i-1} \cdot PH_{i-1}}{Qe_i + Q_{i-1}}, \quad i = 1,2,\ldots,N \qquad (5.19)$$

where for the first zone:

PH_0 = PU, the upstream phosphorus concentration in mg/ℓ.

Q_0 = QU, the upstream flow rate, cfs.

2) <u>Structural Constraints</u>

(i) The parameters θ_1, and θ_2 of the effluent charge rate (Equations (5.7.1) to (5.7.3)) are non-negative, thus:

$$\theta_{1,i} > 0$$

$$\theta_{2,i} > 0;$$

$$i = 1,2,\ldots,N \qquad (5.20)$$

(ii) The treatment levels of BOD and phosphorus, i.e., x_i, and z_i respectively, take values between zero and 100 percent, thus:

$$0 < x_i < 1.$$

$$0 \leq z_i \leq 1. \;;$$

$$i = 1,2,\ldots,N \qquad (5.21)$$

The model can now be comprehensively formulated to consider simultaneously municipal and/or industrial pollution sources at each zone as follows:

$$\text{Minimize} \sum_{\text{zone (i)}} \sum_{\text{source(j)}} \Big[FT_{ij}(WB_{ij}, WP_{ij}, x_{ij}, z_{ij}, \bar{Q}_{ij})$$

$$+ \quad FC_{ij}(WB_{ij}, y_{ij}, x_{ij}) \Big]$$

with respect to x_{ij}, z_{ij}, and y_{ij}; $i=1,2,\ldots,N$, $j=1,2$ such that:

(1) To account for maximum level of BOD:

$$LB_1 = LU + \frac{F1}{Q_1} \sum_{j=1}^{2} WB_{1,j} \frac{(1.0-x_{1,j})}{100} \leqslant MAXBOD_1$$

$$LB_2 = LE_1 + \frac{F1}{Q_2} \sum_{j=1}^{2} WB_{2,j} \frac{(1.0-x_{2,j})}{1.0} \leqslant MAXBOD_2$$

$$\vdots \qquad\qquad\qquad\qquad \vdots$$

$$LB_N = LE_{N-1} + \frac{F1}{Q_N} \sum_{j=1}^{2} WB_{N,j} \frac{(1.0-x_{N,j})}{1.0} \leqslant MAXBOD_N$$

(2) To account for minimum DO level:

$$MDO_1 = \min\{CU + \int_{\tau_o}^{\tau_1} \Big[-K_{1,1} \cdot LB_1 + K_{2,1}(C_{s_1} - C_0(\tau)) + \langle P - R\rangle_1\Big] d\tau\} \geqslant MINDO_1$$

$$MDO_2 = \min\{C_1 + \int_{\tau_1}^{\tau_2} \Big[-K_{1,2} \cdot LB_2 + K_{2,1}(C_{s_2} - C_1(\tau)) + \langle P - R\rangle_2\Big] d\tau\} \geqslant MINDO_2$$

$$\vdots \qquad\qquad\qquad\qquad \vdots$$

$$MDO_N = \min\{C_{N-1} + \int_{\tau_{N-1}}^{\tau_N} \Big[-K_{1,N} \cdot LB_N + K_{2,1}(C_{s_N} - C_{N-1}(\tau)) + \langle P - R\rangle_N\Big] d\tau\} \geqslant MINDO_N$$

(3) To account for maximum level of phosphorus:

$$PH_1 = \frac{EP_{1,1} \cdot Qe_{1,1} + EP_{1,2} \cdot Qe_{1,2} + PU \cdot QU}{Qe_{1,1} + Qe_{1,2} + QU} \leqslant MAXPHR_1$$

$$PH_2 = \frac{EP_{2,1} \cdot Qe_{2,1} + EP_{2,2} \cdot Qe_{2,2} + PH_2 \cdot Q_1}{Qe_{1,1} + Qe_{1,2} + Q_1} \leqslant MAXPHR_2$$

$$\vdots \qquad\qquad \vdots$$

$$PH_N = \frac{EP_{N,1} \cdot Qe_{N,1} + EP_{N,2} \cdot Qe_{N,2} + PH_{N-1} \cdot Q_{N-1}}{Qe_{N,2} + Qe_{N,2} + Q_{N-1}} \leqslant MAXPHR_N$$

(4) Constraints on parameters of effluent charge rate equations:

$$\theta_{1,1,i} \; ; \; \theta_{1,2,i} \geqslant 0$$

$$\theta_{2,1,i} \; ; \; \theta_{2,2,i} \geqslant 0; \quad i = 1,2,\ldots,N$$

(5) Boundary conditions on treatment levels:

$$1 \geqslant x_{i,1} \geqslant 0$$

$$1 \geqslant x_{i,2} \geqslant 0 \; ; \; i = 1,2,\ldots,N$$

$$1 \geqslant z_{i,1} \geqslant 0$$

$$1 \geqslant z_{i,2} \geqslant 0 \; ; \; i = 1,2,\ldots,N$$

5.4 Solution Approach

The objective function and the constraints of the model are highly nonlinear; therefore, a nonlinear optimization technique, is required to solve the problem. In this study, the sequential unconstrained Minimization Technique (SUMT) of Fiacco and McCormick (1968) which is one of the simplest and most efficient nonlinear optimization techniques, is employed. The idea of the technique is to use the original objective function and the constraints to form a sequence of modified unconstrained objective functions which could be minimized by using any appropriate unconstrained multivariate optimization technique. In the context of the model developed in Section 5.3, the problem is first stated as follows:

Minimize:

$$F = \sum_{i=1}^{N} \sum_{j=1}^{2} \Big[FT_{ij}(WB_{ij}, WP_{ij}, x_{ij}, z_{ij}, Q_{ij}) + FC_{ij}(WB_{ij}, y_{ij}, x_{ij}) \Big]$$

Subject to:

$$G_i = LE_i + \frac{F_1}{Q_i} \sum_{j=1}^{2} \left(WB_{ij} - \frac{(1.0 - x_{ij})}{1.0} \right) + MAXBOD_i \geq 0;$$

$$i = 1,2,\ldots,N$$

$$G_k = \min\{C_{i-1} + \int_{\tau_{i-1}}^{\tau_i} -K_{1,i} \cdot LB_i + K_{2,i}(C_{s_i} - C_{i-1}(\tau)) + \langle P - R \rangle_i \Big]\Big\} d\tau - MINDO_i \geq 0;$$

$$k = N+1,\ldots,2N$$

$$G_\ell = \frac{EP_{i,1} \cdot Qe_{i,1} + EP_{i,2} \cdot Qe_{i,2} + PH_{i-1} \cdot Q_{i-1}}{Qe_{i,1} + Qe_{i,2} + Q_{i-1}}$$

$$+ \; MAXPH_i \geqslant 0; \qquad \ell = 2N+1,\ldots,3N$$

$$G_r = x_{ij} \geqslant 0; \qquad r = 3N+1,\ldots,5N$$

$$G_s = 1-x_{ij} \geqslant 0; \qquad s = 5N+1,\ldots,7N$$

$$G_t = z_{ij} \geqslant 0; \qquad t = 7N+1,\ldots,9N$$

$$G_u = 1-z_{ij} \geqslant 0; \qquad u = 9N+1,\ldots,11N$$

$$G_v = \theta_{1,i\,j} \geqslant 0; \qquad v = 11N+1,\ldots,13N$$

$$G_q = \theta_{2,i\,j} \geqslant 0; \qquad q = 13N+1,\ldots,15N$$

where $j=1,2$ indicates number of pollution source at each zone, and $i=1,2,\ldots N$, where N is the number of zones in the river.

The modified objective function, P, is next formulated in terms of the original objective function, F, and a penalty term. This is expressed as follows:

$$P = F + r \sum_{t=1}^{15N} \frac{1}{G_t} \tag{5.22}$$

where r is a positive real number which is re-evaluated to form a monotonically decreasing sequence $r_1 > r_2 > \ldots > 0$. The penalty term is designed so as to insure that the solution is always located in the interior of the constrained region by avoiding to cross the boundaries of the feasible region.

The study has employed the Hooke and Jeeves technique (1961) to solve the modified unconstrained problem. The technique is based on direct search and requires no derivatives. Since the technique assumes a unimodal function, several sets of starting values had to be tried to find the global minimum. For a detailed description of SUMT, and its computational procedures, the interested reader is referred to Appendix B at the end of this report.

CHAPTER VI

APPLICATION OF THE OPTIMIZATION MODEL

6.1 Introduction

The validity of the developed model has been verified by applying it to a hypothetical river basin in two different cases. In the first case (Example 1), three municipal waste treatment plants are considered, which discharge different waste loads into the river. Accordingly, the river is divided into three zones. It is assumed that three plants have the same treatment cost function.

In the second case (Example 2), five pollution sources (two municipal sources, and three industrial sources) are assumed to discharge different amounts of waste in the river which is divided into three zones. The treatment cost function of the industrial source is different from that of the municipal source.

An empirical treatment cost function for municipal sources has been derived and employed in the study. The function is based on the data collected, for the period 1975 - 1977, on municipal wastewater treatment plants in Southern Ontario. The cost function employed for industrial sources is based on the current information for the treatment cost of particular chemical industrial wastes, adopted from literature (e.g., Cost Engineering Journal, 1971).

This chapter is divided into two main parts; in the first part, the treatment cost functions for both municipal and industrial sources are presented. In the case of municipal waste treatment cost function, the data are examined and the development of the cost model is discussed. In the case of industrial waste treatment cost function, the cost models for primary, secondary and tertiary treatment are given.

The second part of this chapter is devoted to a discussion of the input data used in each example (i.e., the river characteristics, types and amounts of waste, water quality standards in each zone, etc.), followed by a detailed presentation of the optimization models for both examples.

It is assumed that municipal sources produce organic and phosphorus waste loads, while industrial sources produce organic loads only. This assumption is based on the fact that most of the phosphorus wastes discharged into rivers originate from domestic activities, (Donald , and Bishop, 1975).

The water quality limits in the first example are held constant throughout the river, whereas they are set differently at each zone in the second example. The water quality limits, in both examples, have been chosen to fall within the acceptable ranges of water quality for public service supplies, (e.g., Guides and Criteria for Water Quality Management in Ontario, Ministry of Environment, June, 1973).

6.2 Development of Waste Treatment Cost Functions

The costs of waste water treatment plants may generally be divided into two main categories: i) capital costs, and ii) operating and maintenance costs (O & M). The capital costs include the cost of land purchases, equipment or structure, installation, and engineering contracting fees. Such costs are generally paid in installments over the useful life of the plant or over an accelerated depreciation period. This cost is usually represented as a fixed part of the cost accounts, (Shah and Reid, 1971). The O & M costs, on the other hand, are the expenses incurred in the day-to-day operation and upkeep of the treatment facilities. This part of the costs is not fixed, but varies with the amount of waste flow, percentage of the treatment required, characteristics of the waste, and other factors. The O & M costs can be divided into: (i) direct costs which include the costs of mainenance, plant chemical supplies, labour and supervision, and utilities; (ii) indirect costs which include the costs of depreciation, insurance, and other general overhead.

Tihansky (1974) indicated that most of the derived functions for operating and maintenance costs pertain only to direct costs, since indirect costs, in most cases, do not constitute a large share of the total operating and maintenance costs. The treatment cost functions, related to municipal and industrial wastes, employed in the present study,are concerned only with the direct portion of operating and maintenance costs.

6.2.1 Cost Function for Municipal Waste Treatment Plants

The derived function of operating and maintenance costs for municipal wastewater treatment plants are based on data collected for 33 municipal wastewater treatment plants in Southern Ontario for the period of 1975-1977. The data include, for each plant, two sets of information. The cost data, such as total salaries, wages, employee benefits, repair and maintenance costs, chemicals, utilities, and other miscellaneous expenses. The details of cost information for each plant are shown in Appendix C1. The technical information regarding the hydraulic capacity, the produced amount of organic and phosphorus waste loads, and the performance of each plant is shown in Appendix C2.

Analysis of Data The collected data presented some diversity regarding the percentages of BOD reduction. The percentages were generally higher than normally expected, particularly at primary and secondary levels. In the course of examining the data, it was found that the estimation for the reduction percentages of BOD are based on calculating the average differences of BOD in samples withdrawn, randomly, from the plant's influent and effluent respectively. Improper sampling methods, or bias regarding the method and/or time of taking the observations might be the reason for such diversity. It was decided, however, to omit such extreme values from the analysis.

Since the data are extended over a four-year period it is important to keep the observations unaffected from the influence of factors extraneous to the cost relationship itself, (Johnston, 1960). For example, observations of the cost values should not be influenced by the variations, from year-to-year, in the prices paid for production factors such as labour and raw materials. A price index is used to diminish such influences. There are many up-to-date price indices available for most production factors of many typical industries (Statistics of Canada, Cat.#62). It is difficult, however, to find an aggregated measure to represent all the variations in prices paid for the factors constituting the operating and maintenance costs of wastewater treatment plants. Therefore, a price index has been extablished based on the collected cost data using the year 1977 as the base year. Only those plants that did not undergo any changes in design capacity or in the method of treatment during the four-year period are considered in the price indices calculation. This is necessary to insure that the variations in costs are only due to variations in prices paid for the operating and maintenance factors. The details of the derivation of the price indices are shown in Appendix C3.

Cost Model The most important factors used to establish operating and maintenance cost functions for municipal wastewater treatment plants have been reported in many studies. (Shah 1970, Michel 1970, and Marsden, et al, 1973). According to these studies, three independent variables are considered in the derivation of the present models: (i) the hydraulic capacity of the plant, $\bar{Q}$, measured in terms of the average daily flow of influents in millions of gallons per day (MGD). (ii) the amount of reduction in BOD, which is a function of the percentage treatment level of BOD, X, and the organic waste load, WB, measured in lbs/day; (iii) the amount of reduction in phosphorus load which, in turn, is a function of the percentage treatment level, Z, and the phosphorus waste load, WP, measured in lb /day.

The three independent variables were plotted against the annual operating and maintenance cost, the dependent variable, in order to determine the type of the relationship between the independent and dependent variables. Identifying these relationships helps in proposing the form of the cost model. Figures 6.1, 6.2 and 6.3 depict these relationships; in each case an exponential relationship may be inferred.

Marsden, et.al (1973) suggested three functional forms that may be used in characterizing cost models:

(i) General Exponential (GE): This form is expressed as follows:

$$c = f_1(x_1, x_2, \ldots, x_n) = e^{\beta_o} \prod_{j=1}^{k} x_j^{\beta_j}; \; x_j > 0 \qquad (6.1)$$

(ii) Generalized Quadratic (GQ): This form is expressed as follows:

$$c = f_2(x_1, x_2, \ldots, x_n) = A\left(\prod_{j=1}^{k} x_j^2\right) \Sigma \frac{\beta_j}{x_j} \Big/ \sum_{j=1}^{k} x_j^4 \qquad (6.2)$$

$$x_i > 0, \; A > 0$$

(iii) Constant Cost Elasticity of Substitution (CCES): This form is expressed as follows:

$$c = f_3(x_1, x_2, \ldots, x_n) = A\left[\sum_{i=1}^{n} \alpha_i x_i^{-B}\right]^{-1/B} \qquad (6.3)$$

$$x_i > 0, \; A > 0, \; B > -1$$

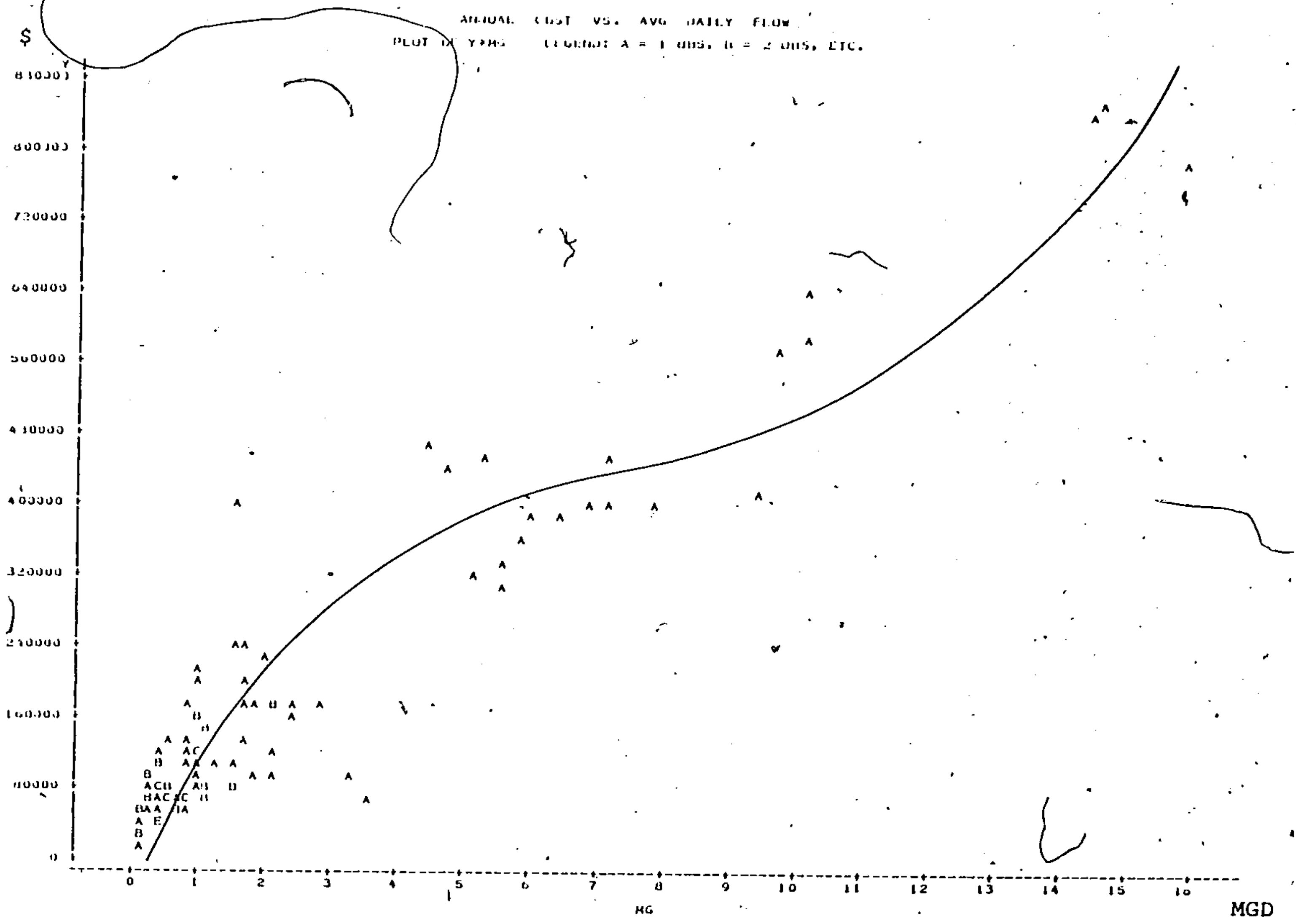
ANNUAL COST VS. AVG DAILY FLOW
PLOT OF Y*HG LEGEND: A = 1 OBS, B = 2 OBS, ETC.
$
Y
880000
800000
720000
640000
560000
480000
400000
320000
240000
160000
80000
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
HG
MGD

Figure 6.1

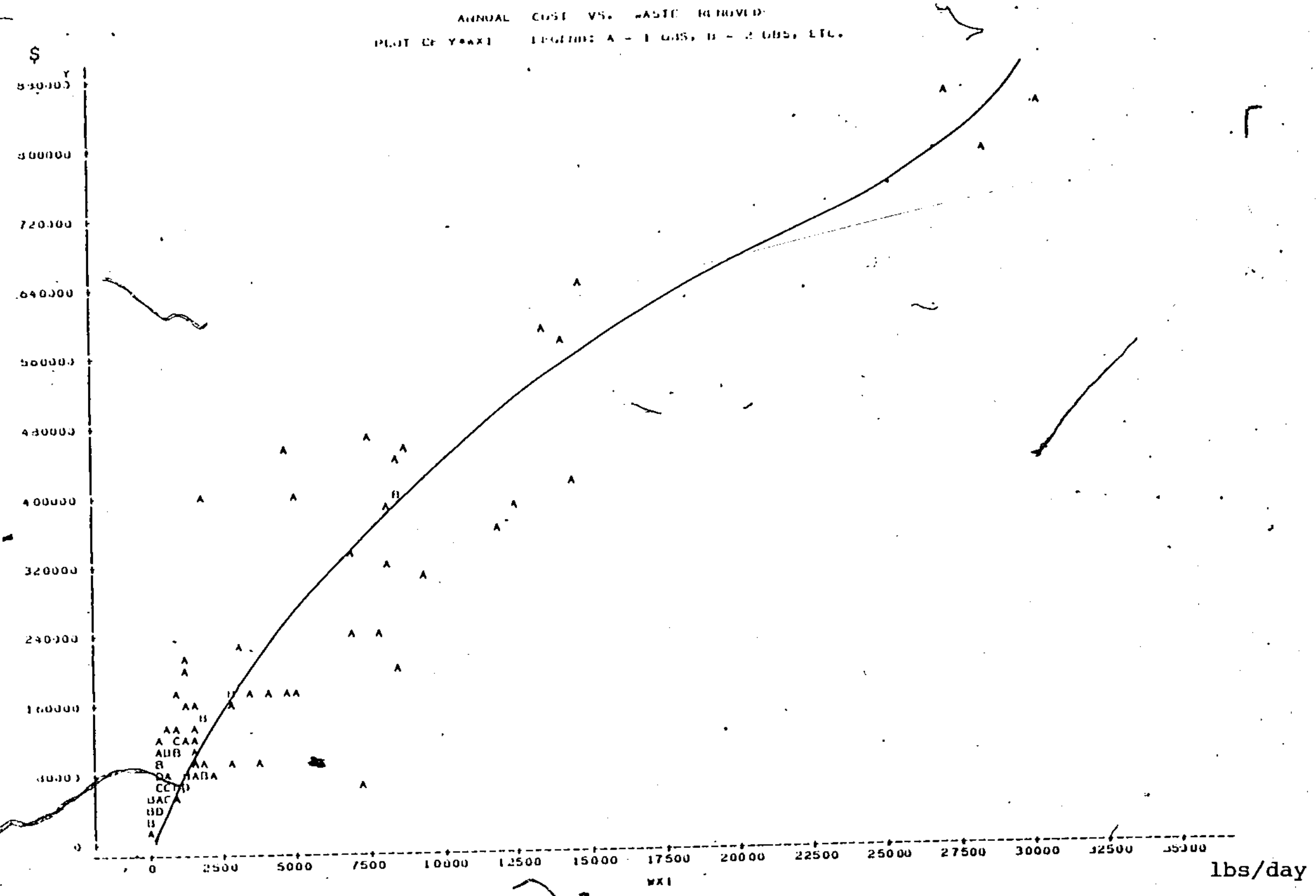
ANNUAL COST VS. WASTE REMOVED
PLOT OF Y*WX1 LEGEND: A = 1 OBS, B = 2 OBS, ETC.
$
Y
880000
800000
720000
640000
560000
480000
400000
320000
240000
160000
80000
0
0
2500
5000
7500
10000
12500
15000
17500
20000
22500
25000
27500
30000
32500
35000
WX1
lbs/day

Figure 6.2

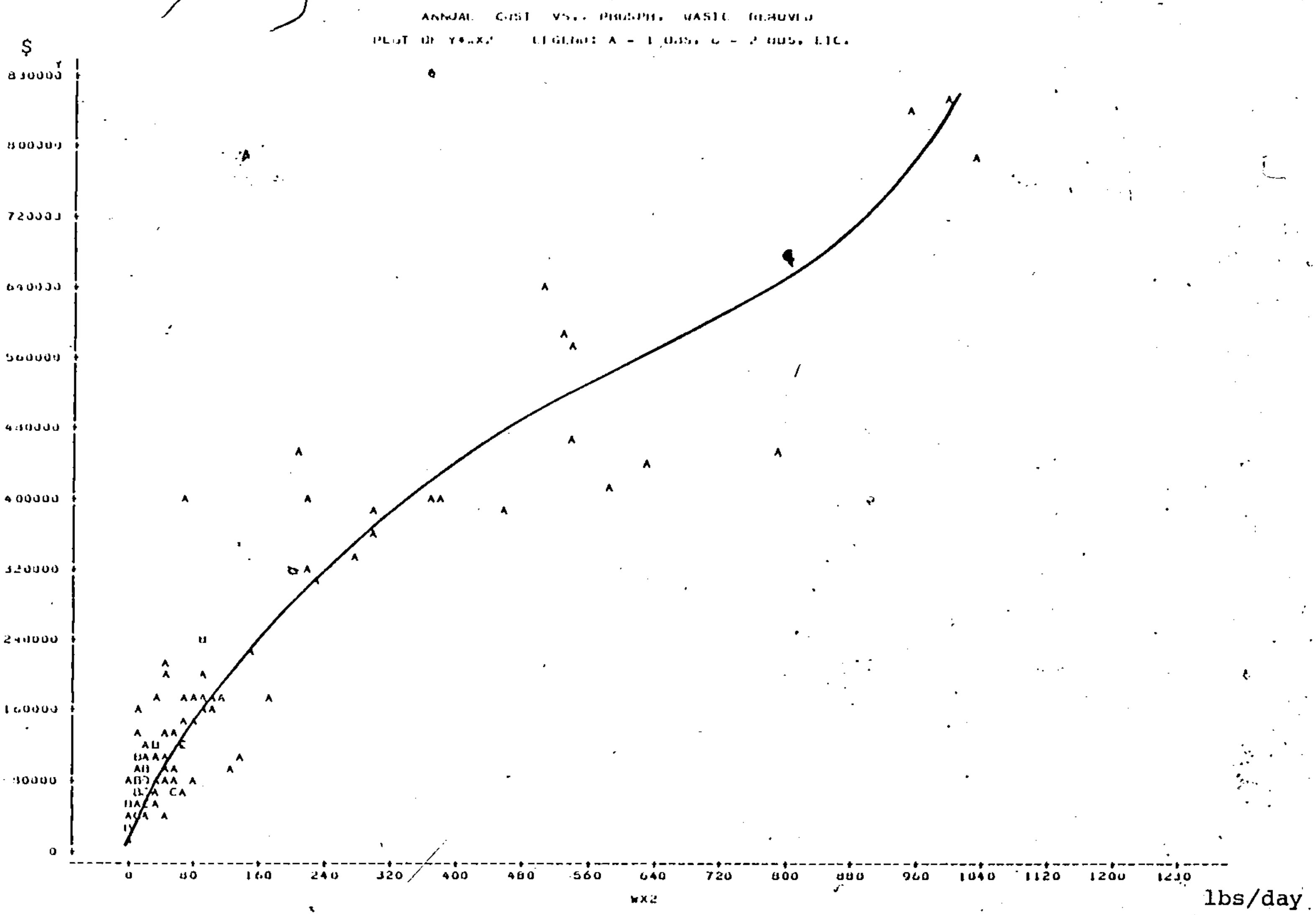
ANNUAL COST VS., PHOSPH. WASTE REMOVED
PLOT OF Y*X2 LEGEND: A = 1 OBS, B = 2 OBS, ETC.
$
Y
880000
800000
720000
640000
560000
480000
400000
320000
240000
160000
80000
0
0
80
160
240
320
400
480
560
640
720
800
880
960
1040
1120
1200
1280
WX2
lbs/day

Figure 6.3

and, $$\sum_{i=1}^{n} \alpha_i = 1, \ \alpha_i > 0 \ (i=1,\ldots,n)$$

where,

c = a cost measure;

x_i = cost factor measures;

e = exponential constant;

α_i, B, A, β_j = parameters of the various functions.

The General Exponential form is easier than the other two forms to deal with for estimation purposes. It is easily transformed into a log-linear form to estimate the parameters involved. Direct, ordinary least-squares method can be applied in this case. Functions in the other two forms may be estimated using nonlinear least-square techniques, or one of several step-wise procedures. These techniques require, however, the evaluation of the derivatives of the dependent variable with respect to function's parameters, which, most of the time, are difficult to obtain.

The General Exponential form has been chosen in the present study to represent the cost function. The function contains the three independent variables given above, and takes the following formulation:

$$c = e^{10.1125} * \bar{Q}^{0.3495} * (WB*X)^{0.1778} * (WP*Z)^{0.0685} \qquad (6.4)$$

The computer program, results, and statistical analysis for the derivation of the cost model are exhibited in Appendix D.

6.2.2 Cost Function for a Typical Chemical Industrial Plant

At present, the available literature on industrial waste treatment costs is not complete because of the diversity of industries in general, and of technological abatement methods, in particular. The Cost Engineering Journal is the main publication devoted exclusively to present cost estimations and cost functions for industrial wastes. The function presented here pertains to chemical industrial plants as reported by Eckenfelder and Barnard (1971). It represents the biological treatment costs at the primary, secondary and tertiary stages as follows:

Primary Treatment Cost Function

$$FT = 909 + 2273\ (1.1/MGD)^{0.5} \qquad (6.5)$$

Secondary Treatment Cost Function

$$FT = 2700 + 2500/(MGD)^{0.67} + UNITS(0.02 - 0.0001*MGD) \qquad (6.6)$$

Tertiary Treatment Cost Function

$$FT = 1500 + 6450\ (1/MGD)^{0.63} \qquad (6.7)$$

where,

FT = Annual operating and maintenance costs in \$/MGD.

MGD = Average flow rate of influents in millions of gallons per day

UNITS = Amount of power consumption in kw.hr/day.

The three cost relationships are functions of the average daily flow of the plant. In addition, the secondary treatment cost function is formulated in terms of the amount of power consumption in kw.hr. The cost functions for the three stages, however, are not formulated so as to include other relevant factors which reflect the strength of the waste. Nevertheless, these functions are satisfactory for the purpose of demonstrating how the model can handle situations involving wastes generated at industrial and municipal sources.

6.3 Model Description for Example 1

6.3.1 Input Data Description

The river basin, in this example, is assumed to receive both organic and phosphorus wastes from three municipalities located along the river. The river basin is thus divided into three zones, as depicted in Figure 6.4. The hydraulic characteristics of the river and parameter values used in the transfer equations (5.1) and (5.2) are given in Table 6.1. It is assumed that the water at the upstream portion is relatively clean. The upstream concentration levels of DO, BOD, and phosphorus are 6,5, and 0.05 mg/ℓ respectively. The local BOD flow rate as well as the stream temperature are assumed constant throughout the segment of the river under consideration. The stream flow rate is 500 cfs, while the stream temperature is 290°K. The residence time at the first, second, and third zone are 1, 1.2, and 1.5 days, respec-

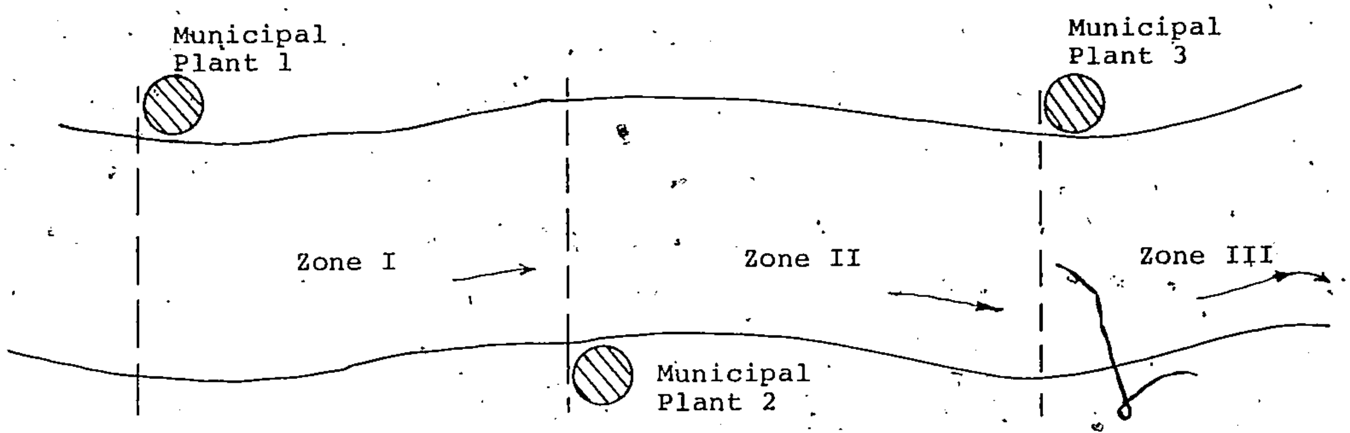

Figure 6.4 The River Basin Configuration - Example 1

tively.

The operating conditions of the waste treatment plants in terms of the average daily flow, and the organic and phosphorus waste loads are shown in Table 6.2. The plant at zone 1 has an average daily flow of 4 MGD, an organic waste load of about 0.2×10^5 lb /day, a phosphorus waste load of 0.8×10^3 lb /day. The second plant has an average daily flow of 5 MGD, an organic waste load of 0.22×10^5 lb /day, a phosphorus waste load of 0.9×10^3 lb /day. The corresponding figures for the third plant are 5 MGD, 0.1×10^5 lb /day, and 0.7×10^3lb/day.

The water quality standards are given in Table 6.3. The maximum allowable BOD concentration in all three zones is 15 mg/ℓ. The minimum allowable DO concentration in all three zones, is 5 mg/ℓ, and the maximum allowable concentration of phosphorus in all the three zones is 0.1 mg/ℓ.

6.3.2 Model Description

In this section, the SUMT formulation of Example 1 is described. The objective function is to minimize:

$$f(XB_1, XB_2, XB_3;\ XP_1, XP_2, XP_3;\ \theta_{11}, \theta_{21};\ \theta_{12}, \theta_{22};\ \theta_{13}, \theta_{23}) =$$

$$\sum_{\text{source } i=1}^{3} \left[e^{10.1125} * \bar{Q}_i^{\,0.3495} * (WB_i * X_i)^{0.1178} * (WP_i * Z_i)^{0.0685} \right]$$

$$+ \sum_{i=1}^{3} \left[(1 - X_i) * WB_i * \theta_{1i} * e^{-\theta_{2i}/(1 - X_i)} \right. \tag{6.8}$$

Subject to the following constraints:

(a) BOD Constraints:

$$g_i = -LB_i + 15.0 \geq 0\ ;\ i=1,2,3$$

Table 6.1

Characteristics of the River and the Parameter Values of the Model for Example 1

Parameter	Description	Numerical Value
LU	Upstream BOD Concentration	5.0 mg/ℓ
CU	Upstream DO Concentration	6.0 mg/ℓ
PU	Upstream Phosphorus Concentration	0.05 mg/ℓ
La	Local BOD Runoff Rate	0.20 mg/ℓ
Q	Stream Flow Rate	500 CFS for Zone 1 500 CFS for Zone 2 500 CFS for Zone 3
α	The Constant in Photosynthesis Respiration Expression	3.46
τ	Residence Time	1 day for Zone 1 1.2 day for Zone 2 1.5 day for Zone 3
T	Stream Temperature	290^{o} K for Zone 1 290^{o} K for Zone 2 290^{o} K for Zone 3
K_3	BOD Adsorption and Sedimentation Coefficient	0.1 day^{-1}

Table 6.2

Operating Conditions of Wastewater Treatment Plants - Example 1

Plant #	Average Daily Flow MGD	Waste Load in lbs/day	
		Organic Waste	Phosphorus Waste
1	4	0.20×10^5	0.8×10^3
2	5	0.22×10^5	0.7×10^3
3	2.5	0.10×10^5	0.6×10^3

Table 6.3

Water Quality Standards - Example 1

Zone	The Desired Water Quality Limits mg/ℓ		
	BOD	DO	Phosphorus
1	15.0	5.0	0.1
2	15.0	5.0	0.1
3	15.0	5.0	0.1

where LB_i is given by Equation (5.11).

(b) DO Constraints:

$$g_k = MDO_i - 5.0 \geqslant 0 \; ; \; k=4,5,6$$

where MDO_i is given by Equation (5.16).

(c) Phosphorus Constraints:

$$g_\ell = -PH_i + 0.1 \geqslant 0 \; ; \; \ell=7,8,9$$

where HP_i is given by Equation (5.19).

(d) Boundary Conditions on X_i:

(1) $g_r = X_i \geqslant 0 \; ; \; r=10,11,12$

(2) $g_s = 1 - X_i \geqslant 0 \; ; \; s=13,14,15$

(e) Boundary Conditions on Z_i:

(1) $g_t = Z_i \geqslant 0 \; ; \; t=16,17,18$

(2) $g_u = 1 - Z_i \geqslant 0 \; ; \; u=19,20,21$

(f) Non-Negativity Conditions on θ_{1j} and θ_{2j}:

$$g_v = \theta_{1i} \geqslant 0 \; ; \; v=22,23,24$$

$$g_q = \theta_{2i} \geqslant 0 \; ; \; q=25,26,27$$

and $i = 1,2,3$

The above optimization model consists of twelve decision variables and twenty-seven constraints. The decision variables represent the BOD treatment levels at the three plants (X_1, X_2, X_3), the phosphorus treatment levels (Z_1, Z_2, Z_3), and the coefficients of the effluent charge formula $(\theta_{11},\theta_{21};\ \theta_{12},\theta_{22};\ \theta_{13},\theta_{23})$. The constraints represent, for each zone, the maximum allowable BOD concentration (3 constraints), the minimum DO concentration (3 constraints), and the maximum limits for phosphorus concentration (3 constraints). The next twelve constraints account for the boundary conditions on the variables representing the organic and phosphorus waste treatment levels, and the remaining six constraints account for the non-negativity of the effluent charge rate coefficients.

The problem has been solved on an IBM 370/3031 computer in 3.31 minutes of CPU time, after 13 iterations of the SUMT procedure. The last iteration represents the final optimum obtained at the required accuracy limit of 10^{-6}, see Appendix . The optimal policy corresponds to a total annual cost of $1,223,334, which includes the effluent charges as well as the treatment costs for all polluters in the basin. The optimal effluent charges are 7.17, 5.37 and 3.18 ¢/lb of BOD discharged in the first, second and third zone, respectively.

The optimal treatment levels of organic waste in the three zones are 58.07%, 68.0% and 78.0%, respectively. The corresponding levels of phosphorus waste treatment in the three zones are 88.9%, 98.9%, and 91%.

6.4 Model Description for Example 2

6.4.1 Input Data Description

This example considers a river basin which receives wastes from both municipal and industrial sources located along the river. It is assumed that the industrial sources generate only organic wastes, while the municipal sources generate not only organic wastes, but also a considerable amount of phosphorus waste, originating mainly from residential areas. Two industrial, and three municipal waste sources are considered, which according to their relative locations, necessitate the division of the river into three zones. Figure 6.5 shows the geographical locations of the plants along the river. The first zone receives wastes from a municipal and an industrial source located across the river from one another. The second zone receives waste from only one municipal source, whereas, the third zone receives wastes from an industrial and a municipal source located across the river from one another.

The hydraulic characteristics of the river, as well as the parameters values used in the transfer equations are given in Table 6.4. The upstream water quality levels are assumed to be 5 mg/ℓ of BOD, 6 mg/ℓ of DO, and 0.05 mg/ℓ of phosphorus. The stream flow rate is 1500 cfs throughout the segment of the river under consideration. The stream temperature, however, has been assumed to change from zone to zone; it is $290^{\circ}K$ in zone 1, $295^{\circ}K$ in zone 2, and $300^{\circ}K$ in zone 3. The residence times are assumed to be 2.5, 2,

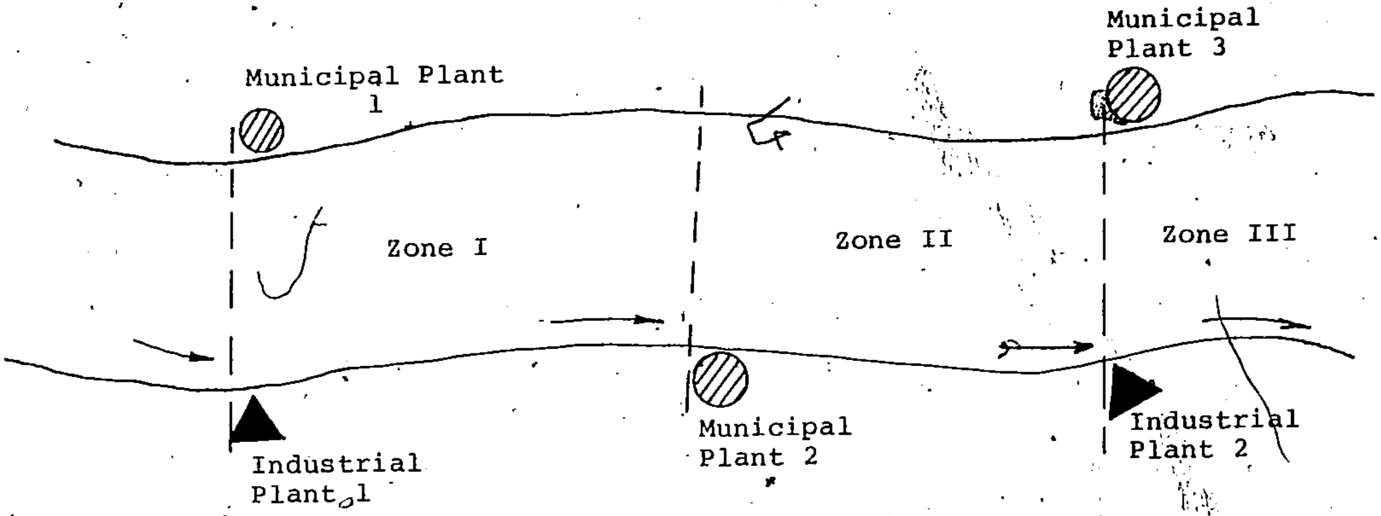

Figure 6.5 The River Basin Configuration - Example 2.

Table 6.4

Characteristics of the River and the Parameter Values of the Model for Example 2

Parameter	Description	Numerical Value
LU	Upstream BOD Concentration	5.0 mg/ℓ
CU	Upstream DO Concentration	6.0 mg/ℓ
PU	Upstream Phosphorus Concentration	0.05 mg/ℓ
La	Local BOD Runoff Rate	0.20 mg/ℓ
Q	Stream Flow Rate	1500 cfs for Zone 1 1500 cfs for Zone 2 1500 cfs for Zone 3
α	The Constant in Photosynthesis Respiration Expression	3.46
τ	Residence Time	2.5 day for Zone 1 2.0 day for Zone 2 3.0 day for Zone 3
T	Stream Temperature	290^{o} K for Zone 1 295^{o} K for Zone 2 300^{o} K for Zone 3
k_3	BOD Adsorption and Sedimentation Coefficient	0.1 day^{-1}

and 3 days at the corresponding zones.

The operating conditions of the municipal and industrial sources, as well as their waste loads, are given in Table 6.5. At the first zone, the municipal source has an average daily flow of 10 MGD, an organic waste load of 0.2 x 10^5lb/day, and a phosphorus waste load of 8.7 x 10^3lb/day. The industrial source has a daily flow of 6 MGD, and about 0.1 x 10^5lb/day of organic waste. At the second zone, the municipal source has an average daily flow of 3 MGD, an organic waste load of 0.4 x 10^4lb/day, and a phosphorus waste load of 0.6 x 10^3lb/day. At the third zone, the municipal source has an average daily flow of 4 MGD, an organic waste load of 0.75 x 10^4lb/day, and a phosphorus waste load of 0.65 x 10^3lb/day. The industrial source in the same zone has 8 MGD average daily flow, and 0.3 x 10^5lb/day of organic waste. The water quality standards are given in Table 6.6. The maximum allowable BOD level are 15, 12 and 15 mg/ℓ at the first, second and third zone, respectively. The corresponding figures for DO concentration are 4.5, 5 and 4 mg/ℓ, and for phosphorus is 0.1 mg/ℓ at the three zones.

6.4.2 Model Description

In this section, the SUMT formulation of the objective function and constraints, for the second example is described. The objective function is to minimize:

$$f(X_1,X_2,X_3,X_4,X_5;\ Z_1,Z_2,Z_3;\ \theta_{11},\theta_{21};\ \theta_{12},\theta_{22};\ \theta_{13},\theta_{23};\ \theta_{14},\theta_{24};\ \theta_{15},\theta_{25}) =$$

$$\sum_{\substack{\text{municipal}\\ \text{source } i=1}}^{3} \left[e^{10.1125} * \bar{Q}_i^{0.3495} * (WB_i * X_i)^{0.1778} * (WP_i * Z_i)^{0.0685} \right]$$

Table 6.5

Operating Conditions of Municipal and Industrial Wastewater Treatment Plants - Example 2

Zone	Source	Average Daily Flow MGD	Waste Load in lb /day	
			Organic Waste	Phosphorus Waste
1	Municipal	10	$0.2 *10^5$	$0.70*10^3$
	Industrial	6	$0.10*10^5$	--
2	Municipal	3	$0.40*10^4$	$0.60*10^3$
3	Municipal	4	$0.75*10^4$	$0.65*10^3$
	Industrial	8	$0.3 *10^5$	--

Table 6.6

Water Quality Standards - Example 2

Zone	The Desired Water Quality Limits mg/ℓ		
	BOD	DO	Phosphorus
1	15.0	4.5	0.1
2	12.0	5.0	0.1
3	15.0	4.0	0.1

$$+\sum_{\substack{\text{industrial}\\ \text{source } j=4}}^{5} \left\{ \begin{array}{l} \left[909.0 + 2273(1.1/\bar{Q}_j)^{0.5}\right]; \quad 0 \leqslant X_j < 0.4 \\ \qquad\qquad\text{or} \\ \left[2700 + (2500.0/\bar{Q}_j^{0.67}) \right. \\ \qquad \left. + 1000.0(0.02 - 0.0001 * \bar{Q}_j)\right]; \\ \qquad\qquad\qquad .4 \leqslant X_j < 0.9 \\ \qquad\qquad\text{or} \\ \left[1500 + 6450(1/\bar{Q})^{0.63}\right]; \quad .9 \leqslant X_j < 1.0 \end{array} \right\}$$

$$+\sum_{\substack{\text{municipal}\\ + \\ \text{industrial}\\ \text{source } k=1}}^{5} \left\{ (1-X_k) * WB_k * \theta_{1k} * e^{-\theta_{2k}/(1-X_k)} \right\} \qquad (6.9)$$

Subject to the following constraints:

(a) BOD constraints:

$$g_1 = -LB_1 + 15.0 \geqslant 0$$

$$g_2 = -LB_2 + 12.0 \geqslant 0$$

$$g_3 = -LB_3 + 15.0 \geqslant 0$$

(b) DO Constraints:

$$g_4 = MDO_1 - 4.5 \geqslant 0$$

$$g_5 = MDO_2 - 5.0 \geqslant 0$$

$$g_6 = MDO_3 - 4.0 \geqslant 0$$

where LB_i and MDO_i; $i = 1,2,3$ are given by Equation (5.13) and (5.16) respectively.

(c) Phosphorus Constraints:

$$g_\ell = -PH_i + 0.1 \geqslant 0$$

where $i=1,2,3$; $\ell=7,8,9$; PH_i is given by Equation (5.19).

(d) Boundary Conditions on X_j:

$$(1)\ g_r = X_j \geqslant 0$$

$$(2)\ g_s = 1 - X_j \geqslant 0$$

where $j=1,2,\ldots,5$; $r=10,11,\ldots,15$; $s=16,17,\ldots,19$.

(e) Boundary Conditions on Z_j:

$$(1)\ g_t = Z_i \geqslant 0$$

$$(2)\ g_u = 1 - Z_i \geqslant 0$$

where $i=1,2,3$; $t=20,21,22$; $u=23,24,25$

(f) Non-Negativity Constraints on θ_{1j} and θ_{2j}:

$$g_v = \theta_{1j} \geqslant 0$$

$$g_q = \theta_{2j} \geqslant 0$$

where $j=1,2,\ldots,5$; $v=26,27,\ldots,30$; $q=31,32,\ldots,35$.

The optimization model of Example 2 consists of eighteen decision variables, and thirty-five constraints. The decision variables represent the BOD treatment levels at all municipal and industrial sources (X_1 through X_5), the phosphorus treatment levels at the three municipal sources (Z_1 through Z_3), and the coefficients of the effluent charge formula (θ_{11} through θ_{25}). The constraints represent for each zone, the maximum allowable BOD concentration (3 constraints), the minimum allowable concentration of DO (3 constraints), and the maximum limits for phosphorus constraints (3 constraints). The next sixteen constraints account for the boundary conditions on the variables, representing the organic and phosphorus treatment levels at the three zones, and the remaining ten constraints account for the non-negativity of the charge rate coefficients.

The problem has been solved on the same IBM 370/3031 computer, in 6.5 minutes of CPU time. The SUMT procedure converged to the optimal solution in twelve iterations at the specified accuracy limits of 10^{-6}. The computer output illustrating the final results of the SUMT procedure is given in Appendix E

The optimal treatment policy has been obtained at a total annual cost of $2,685,790, of which $2,452,890 is the total treatment costs, and $232,900 is the total effluent charges paid to the river basin authority. The optimal rates of the effluent charge levied against the municipal sources in the first, second, and third zone are 2.98, 4.29, and 6.06 ¢/lb of BOD, respectively. The charge rates levied against the industrial sources in the first, and third zones are 2.95, and 2.98 ¢/lb of BOD, respectively.

The optimal treatment levels of organic waste loads in the first zone are 77.7% for the municipal source, and 64.2% for the industrial source. The municipal source in zone 2 is required to treat 60.7% of its waste. Finally, the required treatment levels in zone 3 are 62.7% for the municipal source, and 82.7% for the industrial source. As for the phosphorus wastes, the optimal treatment levels for the three municipal sources at the first zone are 98.5%, 90.5% at the second, and 92.0% at the third zones.

The description of the computer program and the results for the two examples are presented in Appendix E.

CHAPTER VII

DISCUSSION OF RESULTS AND SUGGESTIONS FOR FURTHER STUDIES

7.1 Introduction

This chapter discusses the results of the two applications of the optimization model. The discussion emphasizes the relationships between the effluent charge rates, on one hand, and waste treatment levels, amount and intensity of the discharged wastes, treatment cost functions, and water quality standards, on the other hand. On the basis of the results of the present investigation, a number of conclusions are drawn, and proposals are made, at the end, for further researchs and studies.

7.2 Discussion of Results - Example (1)

This example deals with three municipal waste sources located at three different zones in a river basin. The sources discharge various amounts of organic and phosphorus waste into the river. However, it is assumed that the same treatment cost function applies at each source. The water quality standards are also assumed to be uniform in all three zones.

In Table 7.1, the results of the optimization of the model in Example 1 are presented. In column (1), the total waste load at each zone is given. The optimal treatment level at each source is given in column (2), and the amount of waste treated at each source is calculated in column (3). The cost of treatment, which is based on the amount indicated in column (3) is computed in column (4). The effluent

Table 7.1

Results of the Optimization of Model for Example 1

Zone No.	ORGANIC WASTE LOAD							PHOSPHORUS WASTE LOAD			
	(1) Total Load WB_i lb /day	(2) Optimal Treatment Level X_i %	(3) Amount of Waste Treated (1)x(2) lb /day	(4) Annual Cost of Treatment $/year	(5) Amount of Waste Untreated (1)-(3) lb /day	(6) Effluent Charge Rate ¢/lb	(7) Total Effluent Charge Cost (5).(6) $/year	(8) Total Load WP_i lb /day	(9) Optimal Treatment Level Z_i %	(10) Amount of Waste Treated (8).(9) lb /day	(11) Grand Total Cost (4)+(7)
1	$0.20*10^5$	58.07	$0.116*10^5$	281246	$0.084*10^5$	7.17	219604	$0.8*10^3$	88.9	$0.77*10^3$	500850
2	$0.22*10^5$	68.00	$0.149*10^5$	318414	$0.071*10^5$	5.37	137973	$0.9*10^3$	98.9	$0.88*10^3$	456387
3	$0.10*10^5$	78.00	$0.01 *10^5$	240532	$0.03 *10^5$	3.18	25565	$0.7*10^3$	90.9	$0.63*10^3$	266097

charges apply to the untreated portion of waste (column (5)) and are computed in column (7). It is noted that the highest treatment cost, for example, corresponds to the second source with the highest amount of waste treatment, whereas the lowest level of effluent charges corresponds to the third source, which discharges the least amount of untreated waste. This result is mainly due to the fact that the three sources have the same treatment cost function. The results do not indicate that the concerned relationship follows a general pattern, since the operating conditions at each source, such as the average daily flow, the amount of waste, etc., are different.

The optimal treatment configurations for the organic and phosphorus waste loads are given in columns (2), and (9), respectively. About 58% of the organic load generated at the first source should be treated in order to satisfy the waste quality standards in the first and subsequent zones. At the second source, which has the highest amount of organic waste, the required treatment level is 68%. The corresponding figure for the third source, which generates the least amount of organic waste, is 78%.

The behaviour of the BOD, DO and phosphorus concentrations along the river basin is shown in Figures 7.1(a), (b), and (c), respectively. It is interesting to note that, although the BOD levels in all three zones are below the stipulated standard of 15 mg/ℓ (Figure 7.1(a)), treatment of the organic waste is still necessary due to the stringent standard on DO (5 mg/ℓ) as it is depicted in Figure 7.1(b).

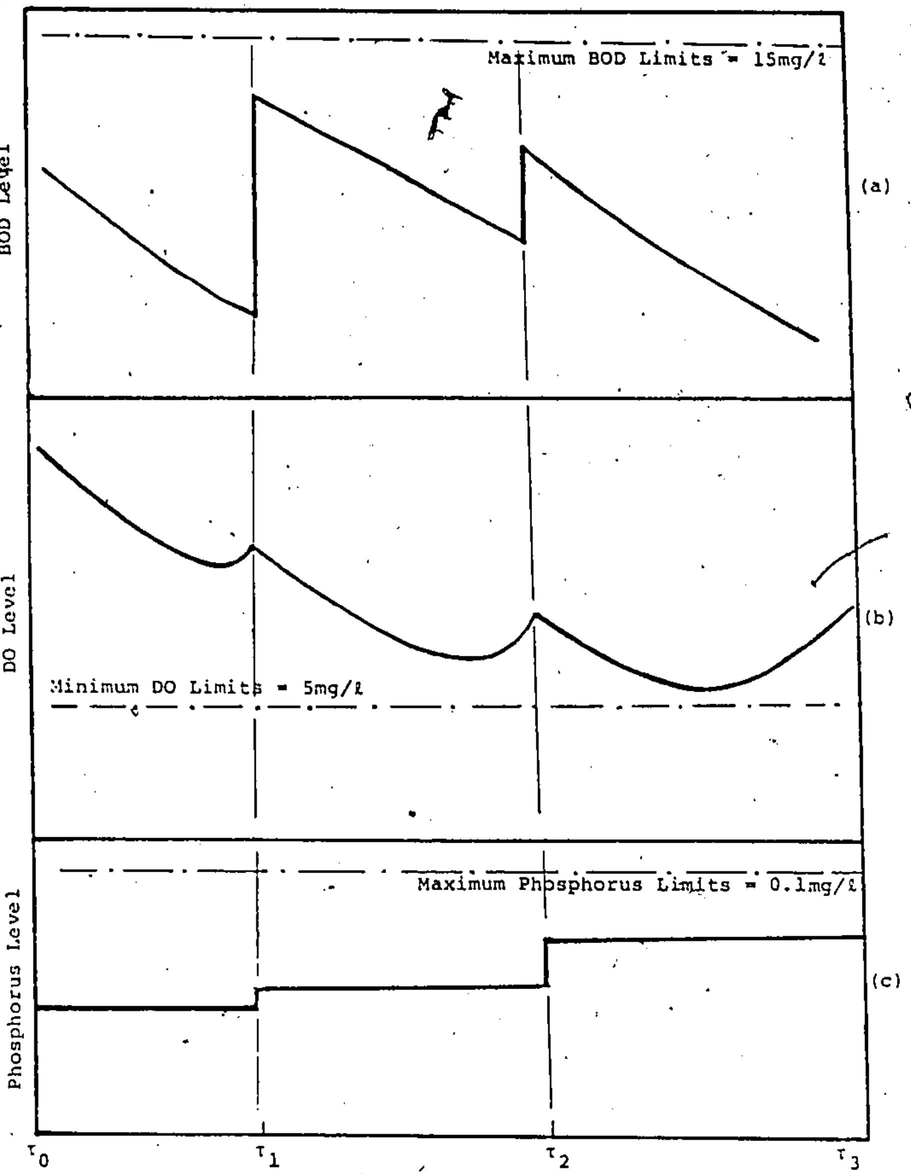

Figure 7.1 (a) BOD Concentration Level
(b) DO Concentration Level
(c) Phosphorus Concentration Level

On the other hand, the results indicate that the phosphorus treatment levels are generally high in the three zones. The treatment levels are 88%, 98%, and 91% at the first, second and third source, respectively. This is expected due to the strict concentrations in the river (0.1 mg/ℓ). The results are in general agreement with current governmental regulations for pollution control, which require at least 80% treatment level of the phosphorus wastes produced at any pollution source. (Environment Canada, Ontario - Conference Proceedings, No. 1, May, 1973).

The behaviour of the phosphorus concentration along the river basin is depicted in Figure 7.1(c), which shows that the phosphorus concentration level changes in step-wise manner.

The effluent charge rates are found to be consistent with the above results. They are also in agreement with the nature of the conditions imposed on the basin system, such as the quality requirements at each zone, the nature of the cost function for each source, and the amount of waste generated at each source. The optimal effluent charge rates for each source are given in column (6) of Table 7.1. The results show that the effluent charge rate for the first zone is 7.17 ¢/lb of BOD discharged. This represents the highest charge rate among the three zones. For the second and third zones, the charges are 5.37 and 3.18 ¢/lb of BOD, respectively. The effluent charge rates are inversely related to the BOD treatment level. The highest charge rate corresponds to the lowest BOD treatment level at the first zone, whereas the lowest charge rate corresponds to the highest treatment level at the third zone.

7.3 Discussion of Results - Example (2)

This example demonstrates the application of the model to a more general case. At each zone in the river, two pollution sources, industrial and/or municipal, are considered. Furthermore, the waste treatment cost functions at various sources are assumed to be different. One or both sources simultaneously discharge their wastes into each zone in the river. Each zone requires different quality limits.

The results of the optimization of the model are presented in Table 7.2. The optimal policy is obtained at the minimum annual cost of $2,685,790. This includes the effluent charge and the treatment cost for each discharger in the basin. In column (11) of Table 7.2, the breakdown of the total cost among different dischargers is given. It is noticed, in this example, that the treatment costs for industrial sources are higher than those for municipal sources. Also, as can be seen from column (7), the effluent charges for industrial sources are less than those for municipal sources. These results will be explained in detail during the course of the discussion.

The optimal treatment configurations for organic and phosphorus wastes at the five pollution sources are given in columns (2), and (9), respectively. The results indicate that the municipal and industrial sources in the first zone have to treat 77.7% and 64.2% of their organic wastes, respec-

Table 7.2

Results of the Optimization of Model for Example 2

Zone No.	ORGANIC WASTE LOAD							PHOSPHORUS WASTE LOAD			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	Total Load WB_i lb/day	Optimal Treatment Level X_i %	Amount of Waste Treated (1)x(2) lb/day	Annual Cost of Treatment $/year	Amount of Waste Untreated (1)-(3) lb/day	Effluent Charge Rate ¢/lb	Total Effluent Charge Cost (5)x(6) $/year	Total Load WP_i lb/day	Optimal Treatment Level Z_i %	Amount of Waste Treated (8)x(9) lb/day	Grand Total Cost (4)+(7)
1(M)†	$0.2*10^5$	77.7	$0.155*10^5$	479884.5	$0.045*10^5$	2.986	48443.4	$0.70*10^3$	98.5	$0.689*10^3$	528327.9
1(I)x	$0.1*10^5$	64.2	$0.064*10^5$	641432.4	$0.036*10^5$	2.958	38576.8	---	---	---	680009.2
2(M)†	$0.4*10^4$	60.7	$0.024*10^5$	227533.7	$0.016*10^5$	4.293	27665.9	$0.60*10^3$	90.5	$0.543*10^3$	255199.6
3(M)†	$0.75*10^4$	62.7	$0.047*10^5$	278950.6	$0.028*10^5$	6.067	61839.7	$0.65*10^3$	92.0	$0.598*10^3$	340790.3
3(I)x	$0.3*10^5$	82.7	$0.248*10^5$	825088.7	$0.052*10^5$	2.987	56374.3	---	---	---	881463.0

N.B. † Indicates Municipal (M)

x Indicates Industrial (I)

tively. The treatment level for the municipal source is higher than that for industrial source, because the former has a more concentrated waste (199.8 mg/ℓ) than the latter (166.5 mg/ℓ). In order to satisfy the water quality standards in the first and subsequent zones, the municipal source, therefore has to treat its waste at a higher level than the industrial source.

The municipal source in the second zone, is the sole pollution source in the zone, and is required to treat about 60.7% of its organic waste.

The optimal organic waste treatment levels for the municipal and industrial sources in the third zone are 62.7% and 82.7%, respectively. The high concentration of BOD at the industrial source (374.7 mg/ℓ) is the reason for the correspondingly high treatment level at this source, relative to the municipal source which has a waste concentration of 187.3 mg/ℓ only.

The behaviours of BOD and DO along the river basin are depicted in Figure 7.2(a) and (b). Again, it is noticed that, although the BOD concentration in all three zones is below the maximum allowable level (15 mg/ℓ), the strict DO concentration requirements (4.5 mg/ℓ in zone 1, 5 mg/ℓ in zone 2, and 4 mg/ℓ in zone 3) necessitate the treatment of the organic waste in all three zones.

As for the phosphorus treatment levels (column (9)), the results indicate that the phosphorus concentration standard in the first zone is attained at a high treatment level of 98.5%. The corresponding standards in zones 2 and 3

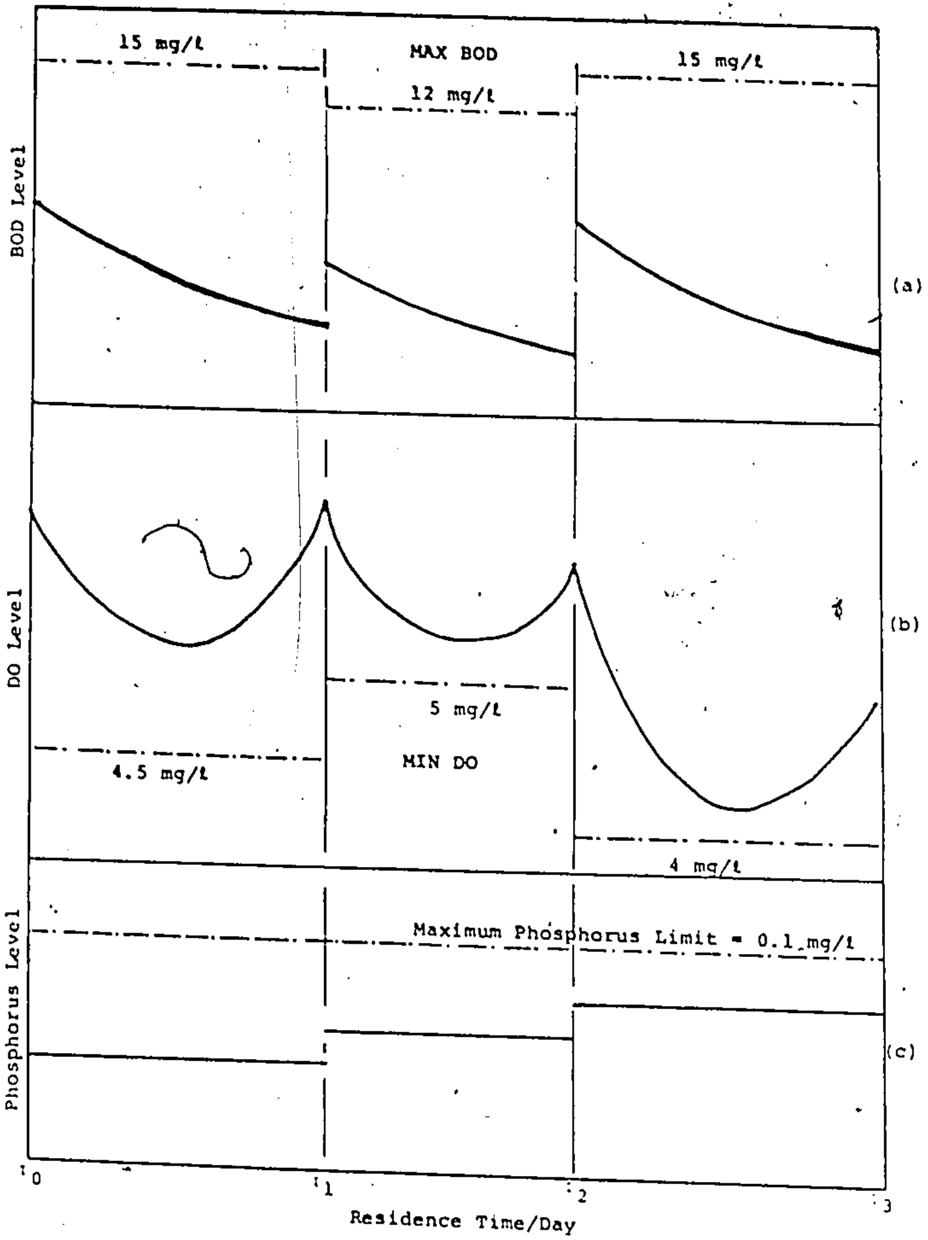

Figure 7.2 (a) BOD Concentration Level
(b) DO Concentration Level
(c) Phosphorus Concentration Level

are attained at treatment levels of 90.5%, and 92.0% for both municipal sources located at the second and third zones, respectively. The high level of phosphorus treatment at the first source is due to the upstream conditions, i.e., the phosphorus concentration of 0.05 mg/ℓ upstream. The behaviour of phosphorus concentration level in the river is shown in Figure 7.2(c), indicating the familiar step-wise variation.

The effluent charge rates to be levied against all the dischargers in the basin are given in column (6). As is evident from these results, dischargers in the same zone may be subject to different charge rates; the municipal source in the first zone, for example, is required to pay 2.98¢/lb of BOD discharged into the river, whereas the industrial source in the same zone is required to pay 2.95¢/lb. The variation in the charge rates, within the same zone, is due to differences in the marginal treatment costs incurred by each source to treat its wastes. To illustrate, while the industrial source at the first zone incurs $641,432.4 annually to treat about $0.1*10^5$ lb/day of BOD, the municipal source incurs less cost ($479,884.5 per year) to treat more waste ($0.2*10^5$ lb/day). The allocation of effluent charges between the two sources, therefore, is in agreement with the idea of imposing a higher rate on the source which incurs smaller treatment cost (Kneese & Schultze, 1975). This tends to encourage such dischargers to treat a larger portion of their wastes than they normally do in the absence of effluent charges.

The municipal source in the second zone is required to pay 4.29 ¢/lb of BOD. In the third zone, the effluent charge rate for the municipal source is 6.06¢/lb of BOD, which is higher than the rate for industrial source which is 2.95 ¢/lb. The difference between the two effluent charge rates may be explained in the same way as was given for the first zone.

7.4 Conclusions

The evaluation of the available literature on water pollution control methods, presented in this study, indicates that the effluent charges strategy is an effective, flexible, and efficient approach to deal with the complicated phenomenon of water pollution. In the present work, the strategy has been incorporated within the framework of a water quality management model, which aims at allocating, optimally, the effluent charge rates among all the polluters using the river basin as waste receptor.

There are two features in the present model which distinguish it from other works seeking the same objective (e.g., Hass (1970) and Taylor (1973)). First, the attainment of the water quality standards throughout the river basin is ensured by explicitly specifying the appropriate constraints in the model's formulation. Moreover, these water quality constraints represent non-linear relations. In previous works, either the water quality constraints have not been explicitly considered, or they have been approximated into linear forms. In both cases, however, there is no guarantee that the required water quality standards are met. This is because the estimation of the optimal effluent charge rates is carried out through an iterative procedure. If water quality standards are not achieved under a given set of effluent charges, the basin authority revises them accordingly. The revised values of effluent charges are transmitted to the polluters in the basin, and then the water quality measures are monitored. The process, which depends entirely on the accuracy of the polluters' response to the charge rates, may take several iterations before it converges on the optimal set of effluent charges. In contrast, the present model determines the effluent charges as well as the levels of waste treatment directly.

Second, the present model determines the effluent charges as a set of non-linear rates as opposed to a set of uniform rates obtained by existing models.

Imposing uniform charge rates on all polluters does not lead to optimal allocation of water resources. For example, a firm which has decided to treat its effluent wastes and/or the incoming water supply for its production processes should, in an efficient resource allocation, face a lower charge rate than a firm which has chosen not to do so. As Tietenberg (1973(a),(b)) has pointed out, theoretically, non-uniform charge rates, rather than uniform rates, constitute the least costly approach to water pollution control.

It is noted that the nonlinearity of the effluent charges is a consequence of the presence of a large number factors which have to be considered in the development of the water of water quality management. These factors may be classified into two categories: (1) factors which describe the variations in stream characteristics (e.g., stream flow rate, stream width and depth, water quality standards, etc.) at different points, and (2) factors which describe the variations in plant performance (e.g., waste treatment costs, amount and intensity of the discharged wastes, levels of waste treatments, etc.) at each pollution source. The consideration of the factors in the first category necessitates the establishment of different zones in the river, so that the model can deal with each zone independently, and determine the optimal charge rate for that zone. On the other hand, consideration of the factors in the second category is reflected in the formulation of the model's objective function and constraints.

The present model, therefore, is developed to account for the complex interactions among the factors mentioned above, and for the nonlinearity of the effluent charges. Accordingly, the results obtained from the applications of the model are to be interpreted in accordance with these interactions. In the first application, for example, the marginal treatment costs for all the polluters as well as the prevailing stream characteristics in all three zones were the same, but the charge rates (7.17, 5.37, and 3.18 ¢/lb of BOD, at the first, second, and third zone, respectively) were different. To interpret these results, one must focus on the overall picture representing the problem, and considering such factors as the intensity of the pollutants generated at each source, the treatment levels at each source, etc. Also, it is noted that in the second applications, not only are the effluent charge rates different in different zones, there may even be different rates applied to a number of polluters in the same zone. These results, which are not obvious beforehand, should be interpreted in the light of the complex interactions among the factors involved. This points to the importance of developing complex mathematical models in order to deal with such complicated problems as environmental pollution control.

The model developed in this study provides a vehicle for the basin authority to determine, for any given set of conditions, the optimal effluent charges. The model is flexible in the sense that any adjustment to input data can easily be implemented. In addition, the data preparations and set up are kept to a minimum, so as to make the computer program easy to use.

7.5 Suggestions for Further Studies

(1) The present model is static in nature, in the sense that it does not consider the effect of time on various parameters under consideration. For instance, it is assumed that the waste discharges at various sources do not vary with time; or, that the flow rate in the river basin

is constant. While such assumptions may not represent the situation realistically, they could be conceived of as representing either the average conditions, or the extreme conditions existing in the river basin.

If the model is based on the average conditions prevailing in the river basin, then the results would be adequate in most cases except when extreme conditions exist. It is, however, possible to run the model under these conditions and determine the corresponding optimal policy.

If, on the other hand, the model is based on the extreme conditions that may prevail in the basin, then the results are applicable in all cases. Nevertheless, the obtained results would place a burden, in different degrees, on the dischargers according to the prevailing feasible conditions. The burden is represented in terms of paying more effluent charges or increasing the levels of the treatment.

To alleviate these shortcomings, a dynamic version of the model may be considered which takes into the account the time-dependency of the model's parameters, hydraulic conditions of stream, and waste discharges. However, the set of partial differential equations that result, are too complicated to handle. Some work for the single-stage model have been developed using the concepts of the maximum principal and optimal control theory (Fan, et al 1973; Fan and Hong, 1972). It is suggested that the application of these concepts to multi-stage models be investigated.

(2) The degradation of water resources is caused, not only by the discharge of organic and inorganic waste, but also by the discharge of "waste heat" in the form of heated water discharges from the cooling processes of various industries, notably the power generation stations. Although the present model does not deal with thermal effects of waste discharges, however, it could be expanded to include the effect of varying temperature on BOD and DO along the river.

(3) It is understood that the phosphorus pollutants have a direct,adverse effect on lakes rather than on rivers. Since lakes are the natural destination of many rivers, in order to halt or decrease their enrichment with plant nutrients (eutrophication process), which accelerates in the presence of phosphorus wastes, the concentration levels of these pollutants in the rivers must be kept within acceptable limits. The present model has recognized this process by imposing a set of control limits on the phosphorus concentration in the river. The model, however, could be extended to include effluent charges to be levied on each unit of the phosphorus waste discharged into the river.

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APPENDICES

APPENDIX A

NUMERICAL SOLUTION OF DIFFERENTIAL EQUATIONS
(RUNGE-KUTTA METHOD)

NUMERICAL SOLUTION OF DIFFERENTIAL EQUATIONS USING THE RUNGE-KUTTA METHOD

An approximate solution could be obtained, for the two differential equations (5.1), and (5.2) given in Chapter V, through a numerical integration method. The Runge-Kutta method is considered one of the most accurate procedures used in such cases. The solution is obtained in the form of a set of values for the dependent variables corresponding to given values of the independent variables (N.G. Bakhoom, 1962). The method can be described as follows:

Assume two simultaneous differential equations:

$$\frac{dy}{dx} = f(x,y,z) \;;\; \frac{dz}{dx} = g(x,y,z) \qquad (1)$$

with initial conditions:

$$x = x_o,\ y = y_o,\ z = z_o$$

where it is required to find y and z for a given value of x.

The Algorithm

(1) Let h: denote the increment in x

k: denote the increment in y

ℓ: denote the increment in z

(2) Compute K and ℓ according to the following expressions:

$$k = \tfrac{1}{6}k_1 + \tfrac{1}{3}k_2 + \tfrac{1}{3}k_3 + \tfrac{1}{6}k_4;$$

$$\ell = \tfrac{1}{6}\ell_1 + \tfrac{1}{3}\ell_2 + \tfrac{1}{3}\ell_3 + \tfrac{1}{6}\ell_4$$

(3) Compute k_1, k_2, k_3, and k_4 as follows:

$$k_1 = h * f(x_o, y_o, z_o)$$

$$k_2 = h * f(x_o + \frac{1}{2}h, y_o + \frac{1}{2}k_1, z_o + \ell_1)$$

$$k_3 = h * f(x_o + \frac{1}{2}h, y_o + \frac{1}{2}k_2, z_o + \frac{1}{2}\ell_2)$$

$$k_4 = h * f(x_o + h, y_o + k_3, z_o + \ell_3)$$

(4) ℓ_1, ℓ_2, ℓ_3, and ℓ_4 are sequentially computed as follows:

$$\ell_1 = h * g(x_o, y_o, z_o)$$

$$\ell_2 = h * g(x_o + \frac{1}{2}h, y_o + \frac{1}{2}k_1, z_o + \frac{1}{2}\ell_1)$$

$$\ell_3 = h * g(x_o + \frac{1}{2}h, y_o + \frac{1}{2}k_2, z_o + \frac{1}{2}\ell_2)$$

$$\ell_4 = h * g(x_o + h, y_o + k_3, z_o + \ell_3)$$

(5) The solution at the new point $x_1 = x_o + h$ is:

$$y_1 = y_o + k$$

$$z_1 = z_o + \ell$$

(6) Set the new value of x such that:

$$x_2 = x_1 + h_1$$

and repeat the procedure from step (2) to step (6) for all points in the domain of x variable.

Application of the Runge-Kutta Method to Solve the Two Simultaneous Differential Equations of the Transformation Equations

The transform equations are expressed as follows:

$$\frac{dC}{d\tau} = g(C, L, T) \qquad (2)$$

$$\frac{dL}{d\tau} = f(L,T) \qquad (3)$$

where C = DO concentration level; mg/ℓ

L = BOD concentration level; mg/ℓ

T = Temperature level; ^{o}K

τ = Residence time; days

Assume: 1) T is constant throughout the zone

2) The initial conditions are $L = L_o$, $C = C_o$, at $\tau = \tau_o$.

3) ΔC is the increment in C;

ΔL is the increment in L;

$\Delta\tau$ is the increment in τ.

Then:

$$\Delta C = \frac{1}{6}D_1 + \frac{1}{3}D_2 + \frac{1}{3}D_3 + \frac{1}{6}D_4$$

$$\Delta L = \frac{1}{6}B_1 + \frac{1}{3}B_2 + \frac{1}{3}B_3 + \frac{1}{6}B_4$$

where:

$$D_1 = \Delta\tau * g(L_o, C_o, T_o)$$

$$D_2 = \Delta\tau * g(L_o + \frac{B1}{2}, C_o + \frac{D1}{2}, T_o)$$

$$D_3 = \Delta\tau * g(L_o + \frac{B2}{2}, C_o + \frac{D2}{2}, T_o)$$

$$D_4 = \Delta\tau * g(L_o + B_3, C_o + D_3, T_o)$$

and

$$B_1 = \Delta\tau * f(L_o, T_o)$$

$$B_2 = \Delta\tau * f(L_o + \frac{B_1}{2}, T_o)$$

$$B_3 = \Delta\tau * f(L_o + \frac{B_2}{2}, T_o)$$

$$B_4 = \Delta\tau * f(L_o + \frac{B_3}{2}, T_o)$$

The solution at the new point $\tau = \tau_o + \Delta\tau$

$$L_1 = L_o + \Delta L$$

$$C_1 = C_o + \Delta C$$

APPENDIX B

SEQUENTIAL UNCONSTRAINED MINIMIZATION TECHNIQUE (SUMT)

SEQUENTIAL UNCONSTRAINED MINIMIZATION TECHNIQUE (SUMT)

The sequential unconstrained minimization technique (SUMT) solves the constrained minimization problem with nonlinear or linear objective function. The technique was originally proposed by Carroll (1959, 1961), and developed further by Fiacco and McCormick (1964 (a), (b), 1965, 1966, 1968).

The general nonlinear programming problem with nonlinear inequality constraints is to choose x to:

$$\begin{aligned} &\text{minimize } f(x), \\ &\quad \text{subject to:} \\ &\qquad g_i(x) \geqslant 0, \quad i = 1,2,\ldots,m \end{aligned} \tag{1}$$

where x is an n-dimensional column vector $(x_1, x_2, \ldots, x_n)^T$. If the variables are required to be non-negative, each constraint is included in the g_i's.

To solve problem (1), function P can be defined as follows:

$$P(x, r_K) = f(x) + r_K \sum_{i=1}^{m} \frac{1}{g_i(x)} \tag{2}$$

where r_K is a positive constant. Subscript K indicates the number of times P function has been set up to solve the problem given by Equation (1). The conditions imposed on the P function are as follows:

1) r_K, $K = 1,2,\ldots,$ is a positive real number and $r_1 > r_2 > \ldots > r_K \ \ldots > 0$. This indicates that $\{r_K\}$ is

a strictly monotonic decreasing sequence and $r_K \rightarrow 0$ as $K \rightarrow \infty$.

2) $R^o = \{x \mid g_i(x) \geqslant 0,\ i = 1,2,\ldots,m\}$ is a non-empty set. This condition indicates that at least one point must exist within the interior of the feasible region.

3) The functions $f(x)$, $g_i(x),\ldots,g_m(x)$ are twice continuously differentiable.

4) The function $f(x)$ is convex.

5) The functions $g_i(x),\ldots,g_m(x)$ are concave.

6) For every finite K, $\{x \mid f(x) \leqslant K;\ x \in R\}$ is a bounded set, where $R = \{x \mid g_i(x) \geqslant 0;\ i = 1,2,\ldots,m\}$.

7) The function $P(x,r_K) = f(x) + r_K \sum_{i=1}^{m} \frac{1}{g_i(x)}$, is, for each $r > 0$, strictly convex for $x \in R^o$. This also indicates that either $f(x)$ is strictly convex or one of $g_i,\ldots,g_m$ is strictly concave.

Practical experience indicates that the problem given by Equation (1) can be solved even when these conditions are not met. The three conditions which are absolutely required to obtain any useful results are conditions (1), (2), and (6). Condition (1) guarantees that the sequential minimization of the P function will eventually lead to the solution of minimization of function $f(x)$. Condition (2) eliminates problems with equality constraints. Condition (6) eliminates problems having local minimum at infinite points.

The characteristics of the P function are as follows:

1) $\lim_{K\rightarrow\infty}\left[r_K \sum_{i=1}^{m} \frac{1}{g_i(x)}\right] = 0$;

2) $\lim_{K\rightarrow\infty} f\left[x(r_K)\right] = u^*$; where $x(r_K)$ is the value of vector x obtained at iteration K, and u^* is a

finite value.

3) $\lim P\left[x(r_K),\ r_K\right] = u^*$;

4) $\{f\ x(r_K)\}$ is a monotonically decreasing sequence.

5) $\sum_{i=1}^{m} \frac{1}{g_i(x)}$ is a monotonically increasing sequence.

The proofs of these characteristics are presented in detail in Fiacco and McCormick (1968).

Intuitive Concept of P Function

The problem is now transformed from a constrained one to an unconstrained problem which can be solved by any of the search techniques. This can be explained as follows:

The term $r_K \sum_{i=1}^{m} \frac{1}{g_i(x)}$ in P function of Equation (2) can be considered as a penalty factor attached to the objective function f(x). By adding the penalty term, the minimization of P function will assure a minimum to be in the interior of the inequality constrained region by avoiding crossing the boundaries of the feasible region. Since the feasible boundary is defined by one or more of the $g_i(x)=0$, $i=1,\ldots,m$, the value of $r_K \sum_{i=1}^{m} \frac{1}{g_i(x)}$ will approach infinity as the value of x approaches one of the boundary lines. Hence the value of x will tend to remain inside the inequality-constrained region.

Computational Procedure

(1) Select the initial value of r_o arbitrarily.

(2) Select a feasible starting point $x^o=(x_1^o, x_2^o, \ldots, x_n^o)$. If the feasible point cannot be easily obtained, select x^o arbitrarily. The computer program can search for a feasible one.

(3) Minimize the P function for the current value of r_K by using the second order optimum gradient method.

(4) Check if a stopping criterion such as:

$$\frac{f[x(r_K)]}{G[x(r_K)]} - 1 < \varepsilon \qquad (3)$$

is satisfied. The solution is the optimal one if the criterion is satisfied; otherwise, go to step 5. The dual value, $G\ x(r_K)$, is defined as:

$$G\Big[x(r_K)\Big] = f\Big[x(r_K)\Big] - r_K \sum_{i=1}^{m} \frac{1}{g_i[x(r_K)]} \qquad (4)$$

(5) Set $K = K + 1$ and $r_{K+1} = r_K/c$ where $c > 1$. Repeat the iteration from step (3).

APPENDIX C

COLLECTED DATA

C1 - Operating and Maintenance Cost

C2 - Performance of the Plants

C3 - Calculation of Index Numbers

TABLE C1(1)

Total Operating and Maintenance Costs For Municipal Wastewater Treatment Plants - 1975

Plant Site	Grand Total	Total Salaries And Employee Benefits	Total Transportation And Communication	Total Repair And Maintenance And Other Services	Total Chemicals And Utilities And Other Supplies	Other Transactions
Dunnville	80432	36969	1591	10020	31852	—
Fergus	42710	23808	1439	5432	12031	—
Kitchener	613929	285624	3111	114538	201873	8783
Simcoe	125984	64076	1455	7733	52720	—
Waterloo	299103	107730	3828	91020	81027	15501
Elmira	46412	33377	1080	151	10124	1680
Burlington	67240	33461	511	14444	18824	—
Campbellford	51867	31629	1396	4528	11510	2804
Huntsville	46799	30592	365	4958	10615	269
Markham	56127	17422	762	23537	14406	—
Newmarket	162219	79152	1109	40130	39790	2038
Richmond Hill	290781	67897	1079	171233	33386	17186
Belleville	329804	159263	2926	58381	76474	32760
Kingston Twp.	123384	64727	2175	11197	45285	—
Sidney Twp.	22319	16283	600	1027	4404	5
Nickel Center	38859	22455	1141	5107	9805	351
North Bay	310622	129528	13725	41927	117133	2315

N.B. All units are dollars

Table C1(1) Continued

Plant Site	Grand Total	Total Salaries And Employee Benefits	Total Transportation And Communication	Total Repair And Maintenance And Other Services	Total Chemicals And Utilities And Other Supplies	Other Transactions
Sturgeon Falls	70539	29388	1339	8243	28469	3105
Valley East	127558	72903	1260	5416	47144	835
Point Edward	45780	26540	1079	2874	15287	——
Port Dover	50306	29982	177	2225	17922	——
Espanola	25266	16718	583	2109	5856	——
Prescott	74592	30369	1089	8020	32069	3045
Trenton	66300	29233	797	14452	21828	——
Chatham	341959	187256	5483	31385	117098	737
Ingersoll	118902	58245	3177	17532	39948	——
St. Mary's	61733	32442	1472	10348	14615	2856
Tillsonburg	88630	48476	1889	13943	24322	——
Van Astra	38132	17665	1508	975	17500	484
Wallaceburg	122443	64476	1801	15605	29304	11257
Brantford	465803	261629	3613	66853	133707	——
Galt	243628	107495	1646	51571	74491	8425
Preston	177549	95612	2459	32436	41690	5352
Delhi	74422	29014	1649	8020	35739	——

TABLE C1(2)

Total Operating and Maintenance Costs for Municipal Wastewater Treatment Plants - 1976

Plant Site	Grand Total	Total Salaries And Employee Benefits	Total Transportation And Communication	Total Repair And Maintenance And Other Services	Total Chemicals And Utilities And Other Supplies	Other Transactions
Point Edward	53267	29756	1101	4652	16898	860
Port Dover	52669	31023	730	2302	20074	—
Prescott	79405	36364	1152	5215	34840	1834
Espanola	33928	24200	987	2216	6525	—
Chatham	376756	195218	5880	37520	137313	825
Ingersoll	121647	56772	2883	13681	43729	4582
St. Mary's	64405	36985	1145	7372	15815	3088
Tillsonberg	110400	54422	2409	19768	33801	—
Van Astra	40260	27475	1724	2122	8759	179
Wallaceburg	172722	72456	4374	39504	52074	4314
Brantford	500570	278562	3372	30855	156330	31451
Galt	254934	119454	1466	50513	78768	4733
Preston	200602	113189	1900	36839	45627	3047
Delhi	62314	32002	1059	10191	19063	—
Dunnville	104355	46591	615	21749	35400	—
Fergus	60146	27564	1990	10064	20528	—

N.B. All units are dollars.

TABLE C1(2) Continued

Plant Site	Grand Total	Total Salaries And Employee Benefits	Total Transportation And Communication	Total Repair And Maintenance And Other Services	Total Chemicals And Utilities And Other Supplies	Other Transactions
Caledonia	90328	34122	1082	29989	25635	—
Hagersville	50515	24670	431	6918	19357	—
Kitchener	668682	308387	3942	154037	192926	9390
Simcoe	151755	76059	869	16514	58313	—
Waterloo	325801	121217	4889	87071	101532	9092
Elmira	55170	34863	1265	4577	14465	—
Burlington DL	72308	36357	416	7449	28086	—
Burlington EG	42277	22130	259	10309	9579	—
Campbellford	72837	49637	3035	4941	13372	2852
Halton Hills	100494	50703	1933	21570	26288	—
Huntsville	77726	43478	2425	9399	18474	3950
Belleville	333530	166023	3345	73966	89969	227
Kingston Twp.	151942	76443	2300	20935	52264	—
Sidney Twp.	15561	9038	592	912	5019	—
North Bay	355286	157006	7475	77720	96801	16284
Sturgeon Falls	89505	47053	1149	9273	26602	4428
Valley East	108517	56069	15107	5124	44366	2853

TABLE C1(3)

Total Operating And Maintenance Costs For Municipal Wastewater Treatment Plants - 1977

Plant Site	Grand Total	Total Salaries And Employee Benefits	Total Transportation And Communication	Total Repair And Maintenance And Other Services	Total Chemicals And Utilities And Other Supplies	Other Transactions
Point Edward	54322	32558	728	3014	16815	1207
Port Dover	67546	33025	——	2860	31719	——
Prescott	79513	39458	1722	6887	29341	2105
Espanola	42861	60332	849	1772	10408	1700
Chatham	447057	213979	7739	76146	149193	——
Ingersoll	149479	75481	8638	16309	44199	4852
St. Mary's	78664	41190	1027	10472	22886	——
Tillsonburg	116697	62374	1919	12416	40056	68
Van Astra	39739	27366	2244	1782	8516	2027
Wallaceburg	216880	81719	5085	58720	59104	12252
Brantford	573841	282967	2918	36826	199658	51472
Galt	314736	135612	2193	67884	103745	5329
Preston	203572	95427	2395	42405	60178	3166
Delhi	59910	28976	525	7961	22448	——

N.B. All units are dollars.

Table C1(3) Continued

Plant Site	Grand Total	Total Salaries And Employee Benefits	Total Transportation And Communication	Total Repair And Maintenance And Other Services	Total Chemicals And Utilities And Other Supplies	Other Transactions
Dunnville	117062	55624	1196	17401	42841	—
Fergus	59481	31164	1221	8883	18213	—
Caledonia	75616	41476	2606	13390	24144	—
Hagetsville	44603	23525	561	5130	16509	—
Kitchener	836386	337149	5025	219238	268944	6030
Simcoe	175343	76241	182	38963	60321	—
Waterloo	362745	123927	10519	91253	130688	6358
Elmira	65635	36051	6746	6744	14239	1856
Burlington DL	81233	43650	481	12356	24806	—
Campbellford	85546	50648	2132	9619	20305	2841
Halton Hills	166407	76037	3342	25660	49657	11711
Huntsville	116687	53077	6029	10410	43619	3552
Belleville	400354	164649	1092	73793	137775	23045
Kingston Twp.	167599	79409	2258	27531	58401	—
Sidney Twp.	25110	15517	1040	473	8080	—
Trenton	87297	43243	1124	6321	36609	—
North Bay	398466	181948	7575	75336	115260	18347
Sturgeon Falls	101191	41355	1000	15943	39940	2953
Valley East	156464	73445	1741	18439	53612	3227

TABLE C2(1)

Plant Loading and Performance For Municipal Wastewater Treatment Plants - 1975

Plant Site	Hydraulic Load	Organic Load		Phosphorus Load		
	Average Daily Flow MGD	BOD lb/day	Reduction Percentage	Po$_4$ lb/day	Influent mg/l	Effluent mg/l
Point Edward	0.27	380	0.68	767.96	22.3	3.8
Port Dover	0.84	1300	0.64	46.08	5.5	1.4
Espanola	0.47	550	0.57	27.66	5.9	4.0
Prescott	0.90	1100	0.57	35.01	3.9	2.1
Trenton	2.2	4300	0.37	107.51	4.9	4.1
Chatham	4.4	7800	0.96	570.46	13.0	0.80
Ingersoll	1.0	1800	0.95	112.7	11.3	2.2
St. Mary's	0.45	1287	0.98	33.66	7.5	1.2
Tillsonburg	0.87	930	0.95	72.88	8.4	0.9
Van Astra	0.17	68	0.95	4.75	2.8	1.4
Wallaceburg	0.82	928	0.93	39.25	4.8	0.7
Brantford	10.1	17000	0.86	644.66	6.4	1.4
Galt	5.5	7500	0.93	362.02	6.6	1.6
Preston	1.5	7200	0.97	104.72	7.0	1.0
Delhi	0.39	630	0.94	32.28	8.3	2.2
Dunnville	0.93	1700	0.98	43.59	4.7	0.6
Fergus	0.67	800	0.97	25.85	7.4	1.3
Kitchener	14.6	30000	0.91	1135.74	7.8	1.0
Simcoe	1.9	5300	0.96	121.27	6.4	0.8
Waterloo	5.8	15000	0.95	665.61	7.1	0.9
Elmira	0.52	8200	0.87	30.60	5.2	2.2
Burlington	1.80	2200	0.89	122.07	6.8	3.5
Campbellford	1.1	550	0.94	15.36	1.4	0.7

TABLE C2(1) Continued

Plant Site	Hydraulic Load	Organic Load		Phosphorus Load		
	Average Daily Flow MGD	BOD lb/day	Reduction Percentage	PO_4 lb/day	Influent mg/1	Effluent mg/1
Huntsville	0.35	320	0.91		7.4	1.2
Markham	1.0	1300	0.85	73.80	7.4	4.9
Newmarket	2.0	3500	0.86	203.45	10.2	2.8
Richmond Hill	1.6	2000	0.95	122.87	7.7	3.7
Belleville	7.1	6000	0.80	644.36	9.1	5.2
Kingston Twp.	1.76	3400	0.86	136.91	7.8	3.9
Sidney Twp.	0.14	151	0.86	4.33	3.1	1.4
Nickel Center	0.34	400	0.88	—	—	—
North Bay	6.6	8300	0.89		7.6	1.4
Sturgeon Falls	1.2	790	0.91	112.7	11.2	2.2
Valley East	0.38	360	0.86		6.7	5.6

TABLE C2(2)

Plant Loading and Performance for Municipal Wastewater Treatment Plants - 1976

Plant Site	Hydraulic Load	Organic Load		Phosphorus Load		
	Average Daily Flow MGD	BOD lb/day	Reduction Percentage	Po_4 lb/day	Influent mg/l	Effluent mg/l
Point Edward	0.42	600	0.64	68.69	16.4	2.7
Port Dover	1.1	2700	0.75	74.6	6.8	1.0
Prescott	0.94	6000	0.62	38.44	4.1	1.7
Espanola	0.48	600	0.65	29.68	6.2	3.8
Chatham	4.7	9000	0.94	674.98	14.4	1.0
Ingersoll	1.2	2000	0.95	87.36	7.3	1.6
St. Mary's	0.55	2000	0.97	51.56	9.4	1.3
Tillsonburg	0.91	800	0.96	66.25	7.3	0.7
Van Astra	0.16	70	0.89	4.79	3.0	0.9
Wallaceburg	1.0	1300	0.93	51.86	5.2	0.9
Brantford	10.1	15000	0.90		6.8	1.6
Galt	5.6	10000	0.95	296.0	5.3	1.2
Preston	1.7	8000	0.96	106.81	6.3	0.9
Delhi	0.44	500	0.92	37.74	8.6	0.7
Dunnville	.96	1100	0.95	42.13	4.4	0.5
Fergus	.87	1000	0.93	68.55	7.9	1.3
Caledonia	.36	400	0.85	22.62	6.3	3.7
Hagersville	.35	200	0.92	14.31	4.1	0.9
Kitchener	15.9	33000	0.86	236.87	7.8	1.3
Simcoe	2.1	4200	0.96	117.28	5.8	0.4
Waterloo	6.0	13000	0.95	371.0	6.5	1.2

TABLE C2(2) Continued

Plant Site	Hydraulic Load	Organic Load		Phosphorus Load		
	Average Daily Flow MGD	BOD lb/day	Reduction Percentage	Po_4 lb/day	Influent mg/l	Effluent mg/l
Elmira	0.57	9000	0.91	33.54	5.9	2.5
Burlington DL	1.50	2000	0.92	106.21	7.1	3.3
Burlington EG	0.86	900	0.88	55.75	6.5	3.9
Campbellford	1.1	400	0.65	16.46	1.1	0.9
Halton Hills	2.1	2000	0.85	123.57	5.9	2.5
Huntsville	0.32	300	0.88	44.64	14.3	1.3
Belleville	7.9	6000	0.84	323.03	4.1	1.3
Kingston	2.12	3000	0.93	103.6	4.9	1.0
Sidney	0.13	80	0.91	5.19	4.0	0.9
North Bay	6.4	9000	0.89	527.7	8.3	1.2
Sturgeon Falls	1.3	1000	0.90	171.14	13.2	2.9
Valley East	0.52	900	0.90	48.75	9.4	6.1

TABLE C2(3)

Plant Loading and Performance for Municipal Wastewater Treatment Plants - 1977

Plant Site	Hydraulic Load	Organic Load		Phosphorus Load		
	Average Daily Flow MGD	BOD lb/day	Reduction Percentage	PO_4 lb/day	Influent mg/l	Effluent mg/l
Point Edward	0.41	652	0.6	50.29	12.3	2.5
Port Dover	0.66	1900	0.78	59.90	9.1	0.9
Prescott	0.96	540	0.38	16.75	3.5	1.3
Espanola	0.48	530	0.57	30.16	6.3	4.2
Chatham	5.30	9500	0.93	845.72	16.0	1.0
Ingersoll	1.12	1900	0.96	99.41	8.9	1.7
St. Mary's	0.54	1500	0.97	32.85	6.1	1.2
Tillsonburg	1.01	1100	0.97	70.51	7.0	0.7
Van Astra	0.17	88	0.96	5.09	3.0	0.4
Wallaceburg	0.99	1200	0.96	55.29	5.6	0.9
Brantford	9.7	15000	0.94	667.50	6.9	1.4
Galt	5.2	8800	0.92	326.72	6.3	2.1
Preston	1.7	8800	0.96	101.73	6.0	0.9
Delhi	0.43	540	0.92	28.73	6.7	0.3
Dunnville	0.98	1400	0.95	40.07	4.1	0.8
Fergus	0.67	770	0.93	43.43	6.7	1.1
Caledonia	0.29	250	0.75	9.54	3.3	1.7
Hagersville	0.37	380	0.96	19.93	5.4	0.3
Kitchener	14.4	33000	0.92	1105.82	7.7	1.1
Simcoe	2.3	5000	0.94	189.89	6.8	0.8
Waterloo	5.9	13000	0.92	353.05	6.0	0.9

TABLE C2(3) Continued

Plant Site	Hydraulic Load	Organic Load		Phosphorus Load		
	Average Daily Flow MGD	BOD lb/day	Reduction Percentage	Po4 lb/day	Influent mg/l	Effluent mg/l
Elmira	0.55	1200	0.93	35.65	6.5	2.5
Burlington DL	1.6	2300	0.91	94.15	5.9	1.0
Campbellford	1.21	834	0.88	35.0	2.9	1.1
Halton Hills	2.4	2900	0.93	148.4	6.2	1.7
Huntsville	0.36	380	0.89	25.49	7.1	1.3
Belleville	7.1	9500	0.89	424.85	6.0	0.7
Kingston Twp.	2.4	3800	0.87	134.04	5.6	1.7
Sidney	0.12	64	0.75	5.74	4.8	1.0
Trenton	3.28	3500	0.84	—	—	—
North Bay	6.90	10000	0.84	440.41	6.4	1.1
Sturgeon Falls	1.50	1100	0.90	49.37	3.3	0.6
Valley East	1.02	1300	0.87	88.5	8.7	7.3

TABLE (C.3)

THE DATA USED FOR CALCULATING THE INDEX NUMBERS FOR MAINTENANCE AND OPERATING COSTS OF THE MUNICIPAL WASTEWATER TREATMENT PLANTS

Plant Site	1975		1976		1977		Index Number		
	Annual Cost	Design Capacity MGD	Annual Cost	Design Capacity MGD	Annual Cost	Design Capacity MGD	75	76	77
Chatham	341959	4.5	376756	4.5	447057	4.5	1.3	1.18	1
Ingersoll	118902	2.25	121647	2.25	149479	2.25	1.25	1.22	1
St. Mary's	61733	0.85	64405	0.85	78664	0.85	1.27	1.22	1
Tillsonburg	88630	1.80	110400	1.8	116697	1.8	1.31	1.05	1
Wallaceburg	122443	1.5	172722	1.5	216880	1.5	1.77	1.25	1
Brantford	465803	12.5	500570	12.5	573841	12.5	1.23	1.14	1
Galt	243628	8.5	254934	8.5	314763	8.5	1.29	1.23	1
Preston	177549	3.71	200602	3.71	203572	3.71	1.14	1.01	1
Delhi	74422	0.7	62314	0.7	59910	0.7	1.45	1.12	1
Dunnville	80432	1.7	104355	1.7	117062	1.7	1.39	.98	1
Fergus	42710	1.1	60146	1.1	59481	1.1	1.15	.83	1
Caledonia	65666	.5	90328	0.5	75616	.5	1.01	.88	1
Hagersville	43807	0.2	50515	0.2	44603	0.7	1.36	1.25	1
Kitchener	613929	13.5	668682	13.5	836386	13.5	1.39	1.15	1
Simcoe	125984	2.0	151755	2.0	175343	2.0	1.20	1.15	1
Burlington	67040	2.5	72308	2.5	81299	2.5	1.21	1.12	1
Campbellford	51867	1.0	72837	1.0	85545	1.0	1.64	1.17	1
Halton Hills	92523	1.5	100494	1.5	166407	1.5	1.79	1.65	1
Huntsville	46799	0.25	77726	0.25	116687	0.25	2.49	1.5	1
South Peel	2321849	50	2971284	50	4001712	50	1.72	1.34	1
Belleville	329804	8	333530	8	400354	8	1.21	1.01	1
Kingston	129384	2.42	151942	2.42	167599	2.24	1.29	1.1	1
Sidney	22319	0.12	15561	0.12	25110	0.12	1.12	1.61	1
North Bay	310622	8	355285	8	398466	8	1.28	1.12	1
Sturgeon Falls	70539	1	88505	1	101191	1	1.43	1.14	1
Valley East	127558	2.5	108517	2.5	156464	2.5	1.22	1.44	1
AVERAGE VALUE OF PRICE INDEX							1.38	1.18	1

APPENDIX D

STATISTICAL ANALYSIS OF THE COST MODEL

STATISTICAL ANALYSIS OF THE COST MODEL

The proposed cost model has been transformed into a Log-Linear form before the direct ordinary least-square method was applied to estimate the parameters of the model β_o, β_1, β_2 and β_3. The estimation process was carried out using the General Linear Model (GLM) computer routine, which was developed at North Carolina State University (1976), and which is part of the SAS (Statistical Analysis System) Library. The procedure uses the principle of the least squares to fit a fixed effect linear model to any type of data.

The statistical results of the GLM procedure are exhibited in the following three tables. Table D.1 exhibits the parameter values of the model and the statistical 'T' test for the estimated mean value of each parameter. The null hypothesis of the test is:

$$H_o \; : \; \beta_j = 0 \; ; \; j = 0,1,2,3$$

that is, the estimated value of the parameter, β_j does not differ significantly from zero. The test rejects the null hypothesis for β_o, β_1, and β_2 at a high level of significance ($\alpha = 0.01$), but accepts the hypothesis for the third parameter β_3 at $\alpha = 0.1$

Table D.2 indicates the results of the 'F' test for the individual effects of the variables in explaining the model. The three variables $\bar{Q}$, $(X * WB)$, $(Z * WB)$ are shown to be significant in explaining the model.

Table D.3 indicates the combined effect of the three independent variables as a whole is shown to be highly significant (at $\alpha = 0.001$) to explain the model. The third variable, the amount of treated phosphorus $(Z * WP)$, has a small coefficient value, β_3, as indicated by the 'T' test. However, the variable itself is highly significant in explaining the model, as it indicated in Tables D.2 and D.3. It was decided, therefore, to keep the third variable in the model.

Table D.1

Parameter Estimates and the Statistical Significance Model For $c = e^{\beta 0} * Q^{\beta 1} * (XB*WB)^{\beta 2} * (XP*WP)^{\beta 3}$

Parameters	Estimate	T Value For $H_o: \beta_i = 0$	$\Pr\{\frac{\beta-0}{\frac{\sigma}{n}} > \lvert T \rvert\}$	STD Error of Estimate
β_0	10.1125	22.30	0.0001	0.4535
β_1	0.3495	3.66	0.0004	0.0668
β_2	0.1778	2.66	0.0091	0.0668
β_3	0.0685	1.03	0.3078	0.0955

Table D.2

The ΔNOVA Table for Individual Effects of Model's Parameters

Source Of Variation	D.F.	Sum Of Squares	Mean Square	F Value	PR F
$\bar{Q}$	1	52.39122	52.39122	367.57	0.0001
XB*WB	1	1.7216	1.7216	12.08	0.0008
XP*WP	1	1.9085	1.9085	13.39	0.0004
ERROR	96	13.6831	0.142533		
CORRECTED TOTAL		69.7046			

Table D.3

The ΔNOVA Table for Combined Effect of Model's Parameters

Source of Variation	D.F.	Sum of Squares	Mean Square	F Value	PR F
Model's Parameters	3	56.02140	18.6780	131.01	0.0001
Error	96	13.6831	0.1425		
Corrected Total	99	69.7046			

```
1                                     S T A T I S T I C A L   A N A L Y S I S   S Y S T E M
NOTE: THE JOB COST HAS BEEN RUN UNDER RELEASE 76.6D OF SAS AT THE UNIVERSITY OF WINDSOR.

1          DATA ;   INPUT YEAR  IN  EF  Y  WD  PRD  MG  PD  ;
2          IF  YEAR=3   THEN  Y=Y*1.38 ;
3          IF  YEAR=2  THEN  Y=Y*1.18  ;
4          IF  YEAR=1  THEN  Y=Y  ;
5          PRP=(IN-EF)/IN  ;
6          Q=MG*1.855  ;
7          WP=(Q*IN)/0.186  ;
8          WX1=WD*PRD  ;
9          WX2=WP*PRP   ;
10         LY=LOG(Y)  ;  X1=LOG(MG)  ;  X2=LOG(WX1)   ;   X3=LOG(WX2)  ;
11         CARDS ;

NOTE: DATA SET WORK.DATA1 HAS 100 OBSERVATIONS AND 17 VARIABLES. 52 OBS/TRK.
NOTE: THE DATA STATEMENT USED 0.59 SECONDS AND 102K.

112        PROC   GLM  ;
113        TITLE  ************************************;
114        TITLE 1 DERIVED  COST  MODEL  FOR  MMUNICIPAL* ;
115        TITLE 2   WASTEWATER  TREATMENT  PLANT  IN   * ;
116        TITLE 3         SOUTHERN  ONTARIO             * ;
117        TITLE 4 ***********************************  *;
118        TITLE 5 Y=  ANNUAL  TOTAL  OPERATING  COST    *;
119        TITLE 6 MG= AVERAGE  DAILY  FLOW  IN  MILLIO *;
120        TITLE 7 X1= PERCENTAGE  REMOVAL  OF  BOD      *;
121        TITLE 8 X2= PERCENTAGE  REMOVAL  OF  PO4 ;   *;
122        TITLE 9 W1= AMOUNT  OF  ORGANIC  WASTE  LOAD  LB/DAY  ;
123        TITLE 10 W2=  AMOUNT  OF  PHOSPHORUS  WASTE  LOAD  ;
124        MODEL  LY=  X1  X2  X3  /P  CLM  ;

NOTE: THE PROCEDURE GLM USED 1.22 SECONDS AND 158K AND PRINTED PAGES 1 TO 2.

125        PROC  PLOT  ;  PLOT  Y*MG   ;
126        TITLE  ANNUAL  COST  VS.  AVG  DAILY  FLOW ;

NOTE: THE PROCEDURE PLOT USED 0.42 SECONDS AND 120K AND PRINTED PAGE 3.

127        PROC  PLOT  ;  PLOT  Y*WX1  ;
128        TITLE  ANNUAL  COST  VS.  WASTE  REMOVED  ;

NOTE: THE PROCEDURE PLOT USED 0.46 SECONDS AND 120K AND PRINTED PAGE 4.

129        PROC  PLOT  ;  PLOT  Y*WX2  ;
130        TITLE  ANNUAL  COST  VS.  PHOSPH.  WASTE  REMOVED  ;

NOTE: THE PROCEDURE PLOT USED 0.46 SECONDS AND 120K AND PRINTED PAGE 5.

NOTE: SAS USED 158K MEMORY.

NOTE: BARR, GOODNIGHT, SALL AND HELWIG
      SAS INSTITUTE INC.
      P.O. BOX 10066
      RALEIGH, N.C. 27605
```

```
                         10 W.E=  AMOUNT  OF  PHOSPHORUS  WASTE  LOAD

                                GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: LY
OBSERVATION        OBSERVED          PREDICTED          RESIDUAL        LOWER 95% CL      UPPER 95% CL
                     VALUE             VALUE                              FOR MEAN          FOR MEAN

    45           11.17004466       11.55667971       -0.38663505       11.45515619       11.65820323
    46           10.99554004       10.83830682        0.15723322       10.70780171       10.96881194
    47           12.09553710       12.16955690       -0.07401981       12.07114562       12.26796819
    48           12.65955648       12.60479022        0.05476626       12.25003957       12.95954087
    49           11.08368904       11.31185789       -0.22816884       11.20612547       11.41759031
    50           12.09676859       12.08832802        0.00844057       12.00186339       12.17479265
    51            9.81803750       10.25722500       -0.43918750       10.08877140       10.42567861
    52           12.85797144       12.77880548        0.07916596       12.63803783       12.91957312
    53           11.56756421       11.74924106       -0.18167685       11.57934258       11.91913953
    54           11.76017656       11.26946838        0.49070818       11.15318303       11.38575374
    55           13.01044138       12.76865093        0.24179045       12.58703969       12.95026218
    56           11.91491119       11.78801751        0.12689368       11.68367994       11.89235500
    57           11.27294090       11.41648963       -0.14354873       11.26024748       11.57273177
    58           11.66733611       11.64030540        0.02703071       11.54486299       11.73574782
    59           10.59008835       10.38377713        0.20631123       10.22381713       10.54373712
    60           12.28709948       11.62549834        0.66160115       11.54755852       11.70343816
    61           13.26010763       13.03569730        0.22441034       12.88140483       13.18998976
    62           12.65957525       12.65792877        0.00164648       12.53388907       12.78196848
    63           12.22377503       12.21142240        0.01235263       12.01300720       12.40983759
    64           11.00059872       11.14848128       -0.14788256       11.02577795       11.27118460
    65           11.67045899       11.62257191        0.04788708       11.53282738       11.71231643
    66           10.99341221       11.37707760       -0.38366538       11.28008870       11.47406649
    67           10.70569091       11.01518017       -0.30948926       10.89867884       11.13168150
    68           13.63684551       13.34974079        0.28710472       13.17204327       13.52743831
    69           12.07449933       12.32688485       -0.25238552       12.22799065       12.42577906
    70           12.80145539       12.79341504        0.00804035       12.66044706       12.92638301
    71           11.09186437       11.36308542       -0.27122105       11.23260312       11.49356772
    72           11.30507685       11.93521331       -0.63013647       11.85683961       12.01358701
    73           12.02219187       12.14396368       -0.12177181       12.05567289       12.23225447
    74           12.90010443       12.81177591        0.08832853       12.67121255       12.95233927
    75           10.13102145       10.16364849       -0.03262703        9.96964190       10.35765507
    76           11.37707138       12.28181811       -0.90474673       12.17018728       12.39344894
    77           12.89537745       12.80077510        0.09460236       12.66286851       12.93868169
    78           11.52476510       11.73426753       -0.20950243       11.62201666       11.84651839
    79           11.66682183       10.97398879        0.69283304       10.84409770       11.10387987
    80           11.95058123       11.52144492        0.42913631       11.30428465       11.73860520
    81           12.02932950       12.17036307       -0.14103357       12.07912726       12.26159888
    82           11.35679783       11.56344729       -0.20664946       11.42459490       11.70229968
    83           11.23342318       10.71554891        0.51787427       10.56132356       10.86977426
    84           12.88300253       12.72068791        0.16231462       12.53157145       12.90980437
    85           13.57857833       13.37812560        0.20045273       13.19583203       13.56041917
    86           11.63336774       11.98686749       -0.35349975       11.88552810       12.08820687
    87           11.42645954       10.96109673        0.46536281       10.74997336       11.17222009
    88           11.36149379       11.26379293        0.09770086       10.98156068       11.54602518
    89           10.81751292       11.45945186       -0.64193893       11.36348746       11.55541625
    90           11.57671721       10.94504161        0.63167560       10.82748628       11.06259695
    91           10.76862814       10.28964211        0.47898603       10.11214127       10.46714295
    92           12.04514022       12.01887224        0.02626798       11.92550836       12.11223612
    93           11.75729604       11.86189628       -0.10460024       11.76016545       11.96362711
    94           11.43512823       11.94755255       -0.51242431       11.86118193       12.03392316
    95           11.41442007       10.92474107        0.48967900       10.81373820       11.03574394
    96           11.00963240       10.73163346        0.27799894       10.59698938       10.86627753
    97           11.06739682       11.66418237       -0.59678555       11.30091367       12.02745108
    98           13.28901717       13.04101390        0.24800327       12.88286815       13.19915965
    99           11.35420449       11.86790349       -0.51369900       11.78900329       11.94680370
   100           11.71430918       11.55631789        0.15799129       11.44138046       11.67125532

            SUM OF RESIDUALS                                0.00000000
            SUM OF SQUARED RESIDUALS                       13.68318781
            SUM OF SQUARED RESIDUALS - ERROR SS            -0.00000000
            FIRST ORDER AUTOCORRELATION                     0.10898445
            DURBIN-WATSON D                                 1.77548176
```

VERY POO

```
                                     10 W2=  AMOUNT  OF  PHOSPHORUS  WASTE  LOAD
                                       GENERAL  LINEAR  MODELS  PROCEDURE

DEPENDENT VARIABLE: LY

SOURCE              DF       SUM OF SQUARES        MEAN SQUARE       F VALUE        PR > F        R-SQUARE         C.V.

MODEL                3          56.02142022        18.67380674        131.01        0.0001        0.803698       3.2154

ERROR               96          13.68318781         0.14253321                      STD DEV                     LY MEAN

CORRECTED TOTAL     99          69.70460802                                      0.37753570                 11.74137153

SOURCE              DF            TYPE I SS      F VALUE      PR > F         DF        TYPE IV SS      F VALUE      PR > F

X1                   1          54.43486639       381.91      0.0001          1        1.90856455        13.39      0.0004
X2                   1           1.43674007        10.08      0.0020          1        1.00933010         7.08      0.0091
X3                   1           0.14981376         1.05      0.3078          1        0.14981376         1.05      0.3078

                                                T FOR H0:     PR > |T|          STD ERROR OF
PARAMETER                 ESTIMATE          PARAMETER=0                          ESTIMATE

INTERCEPT              10.11253225                22.30       0.0001            0.45353281
X1                      0.34951540                 3.66       0.0004            0.09551485
X2                      0.17782478                 2.66       0.0091            0.06682419
X3                      0.06852198                 1.03       0.3078            0.06683625

OBSERVATION           OBSERVED           PREDICTED             RESIDUAL        LOWER 95% CL       UPPER 95% CL
                         VALUE               VALUE                               FOR MEAN           FOR MEAN

      1            11.14796313         11.42295715          -0.27499401        11.32382720        11.52208710
      2            10.45929840         10.88770687          -0.42840847        10.71304890        11.06236484
      3            11.05368609         12.27797338          -1.22428729        11.98358083        12.57236593
      4            11.54187204         11.41171709           0.13015496        11.28142958        11.54200459
      5            11.42402868         11.89538519          -0.47135651        11.66023838        12.13053200
      6            10.66571760         10.99534923          -0.32963163        10.86221340        11.12848505
      7            11.28367581         10.96406210           0.31961371        10.81962243        11.10850178
      8            11.12056413         11.48624557          -0.36568144        11.35597456        11.61651657
      9            10.72154784         11.08285129          -0.36130344        10.90907234        11.25663024
     10            11.04858672         11.03252053           0.01606620        10.78977371        11.27526732
     11            11.03729676         11.69342102          -0.65612426        11.60637926        11.78046278
     12            11.44783106         11.76623082          -0.31839976        11.54641239        11.98604925
     13            10.59751035         11.08421655          -0.48670620        10.97311372        11.19531937
     14            13.06452962         12.64727994           0.41724968        12.49012125        12.80443864
     15            12.00813840         11.74521273           0.26292567        11.61812371        11.87230176
     16            11.35265741         11.33208275           0.02057466        11.16290707        11.50125842
     17            10.87089260         10.29364887           0.57724373        10.10188603        10.48541171
     18            12.03748439         11.48602672           0.55145767        11.40666429        11.56538916
     19            13.37360158         13.05249919           0.32110238        12.89533431        13.20966407
     20            12.72548125         12.66682069           0.05866056        12.54242244        12.79121895
     21            12.40908541         12.13639418           0.27269122        11.94764064        12.32514772
     22            11.53959038         11.13561121           0.40397917        11.00461553        11.26660688
     23            11.61725089         11.65560825          -0.03835736        11.55390255        11.75731394
     24            10.98427186         11.38266775          -0.39839589        11.29676897        11.46856653
     25            12.06599369         12.17416231          -0.10816862        12.04801547        12.30030916
     26            12.93062677         13.03265493          -0.10202815        12.87984436        13.18546550
     27            11.07546554         11.43763096          -0.36216542        11.34052808        11.53473384
     28            11.17852153         11.39658550          -0.21806398        11.15728309        11.63588791
     29            11.07570061         10.96526199           0.11043862        10.82998934        11.10053464
     30            11.25745576         11.57903661          -0.32158085        11.47770955        11.68036366
     31            13.64971806         13.33866053           0.31105754        13.16093949        13.51638156
     32            12.31878605         12.12135464           0.19743142        12.01968493        12.22302434
     33            12.90240918         11.90410382           0.99830536        11.82611974        11.98208791
     34            13.02833732         12.66978333           0.35855399        12.49169728        12.84786939
     35            10.33527711         10.34995318          -0.01467607        10.16623378        10.53367258
     36            13.00486748         12.70298455           0.30188294        12.53626532        12.86970378
     37            11.87439313         11.80811052           0.06628261        11.71885870        11.89736234
     38            11.23846099         11.50975838          -0.27129739        11.32075863        11.69875813
     39            11.77737985         11.54143632           0.23594353        11.42955884        11.65331381
     40            12.22495308         11.63219277           0.59276032        11.55517853        11.70920701
     41            12.61427441         12.71569553          -0.10142110        12.58510279        12.84628822
     42            12.37459256         12.19839049           0.17620207        12.01293935        12.38384163
     43            11.20545584         11.15883449           0.04662135        11.01895200        11.29871698
     44            11.72106827         11.58251456           0.13855371        11.50563620        11.65939292
```

APPENDIX E

DESCRIPTION OF THE COMPUTER PROGRAM

(1) Program Description

(2) Flow Chart

(3) Program List

(4) Program Set-Up and Results For Example (1)

(5) Program Set-Up and Results For Example (2)

DESCRIPTION OF THE COMPUTER PROGRAM

The computer program used in this study has been developed to determine the optimal charge rates as well as the optimal treatment configuration at each source of pollution. The computer program consists of a main program, three special-purpose subroutines, and five user-supplied subroutines. The main program contains the optimization algorithm, which is based on the search developed by Hooke and Jeeves (1961). It performs the minimization procedure on the unconstrained objective function, supplied to it by the SUMT procedure. The following three special-purpose subroutines transform the constrained optimization problem into an unconstrained one:

(1) SUBROUTINE WEIGH is used to compute, for the initial solution, the total weigh of violation to the inequality constraints. The weigh is used to adjust the initial solution to be located in the interior of the constrained region. The search procedure for the global minimum, therefore, starts at a feasible point.

(2) SUBROUTINE PENAT is used to calculate the penalty term for the modified objective function in the SUMT formulation.

(3) SUBROUTINE BACK is a huristic program used to pull the current infeasible solution back into the feasible region during the search procedure.

The five user-supplied subroutines are:

(1) SUBROUTINE READIN which reads any additional data necessary for the computation purpose.

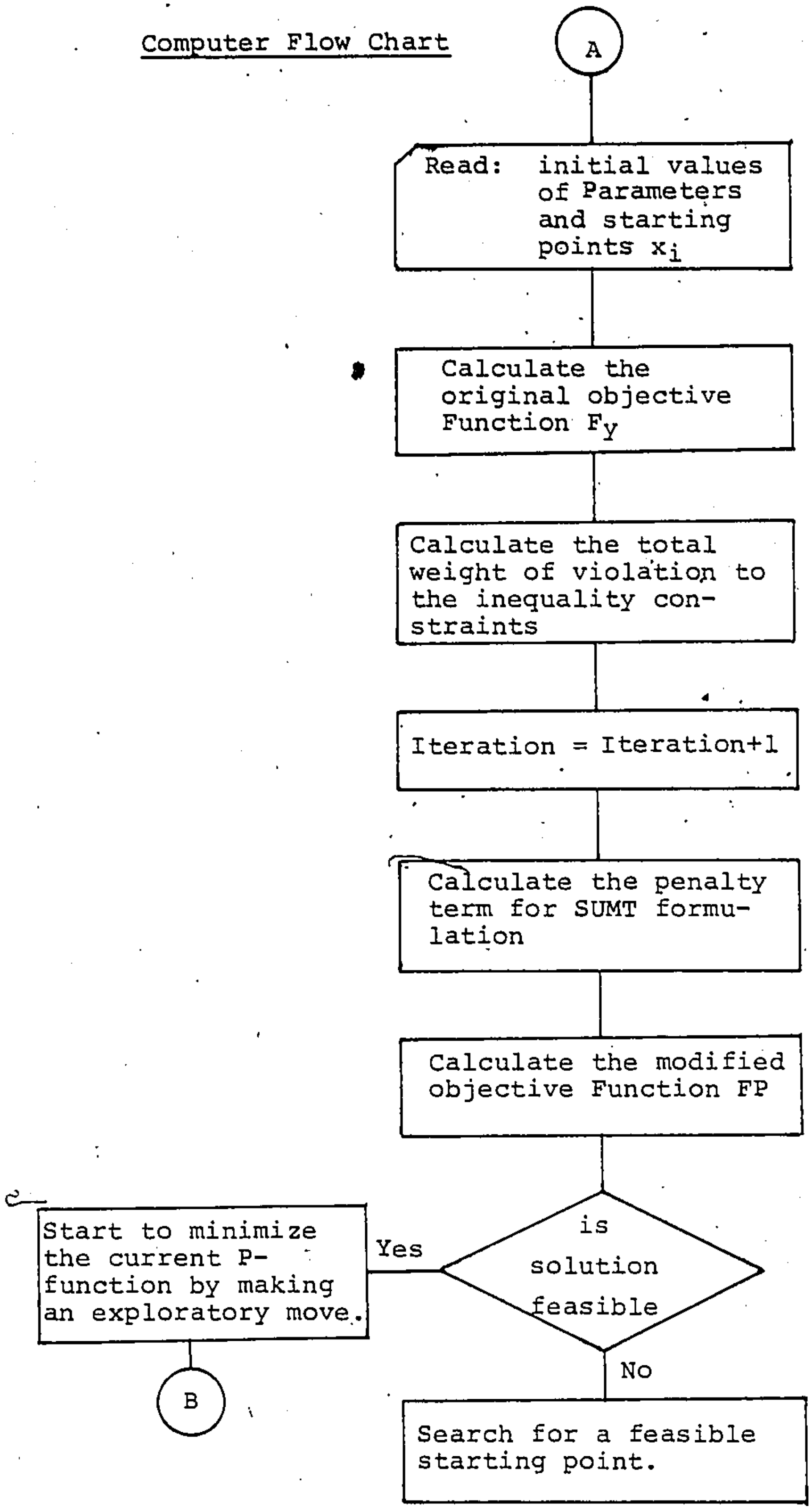
(2) SUBROUTINE OUTPUT which is used to print out any additional information at any stage of the search procedure.

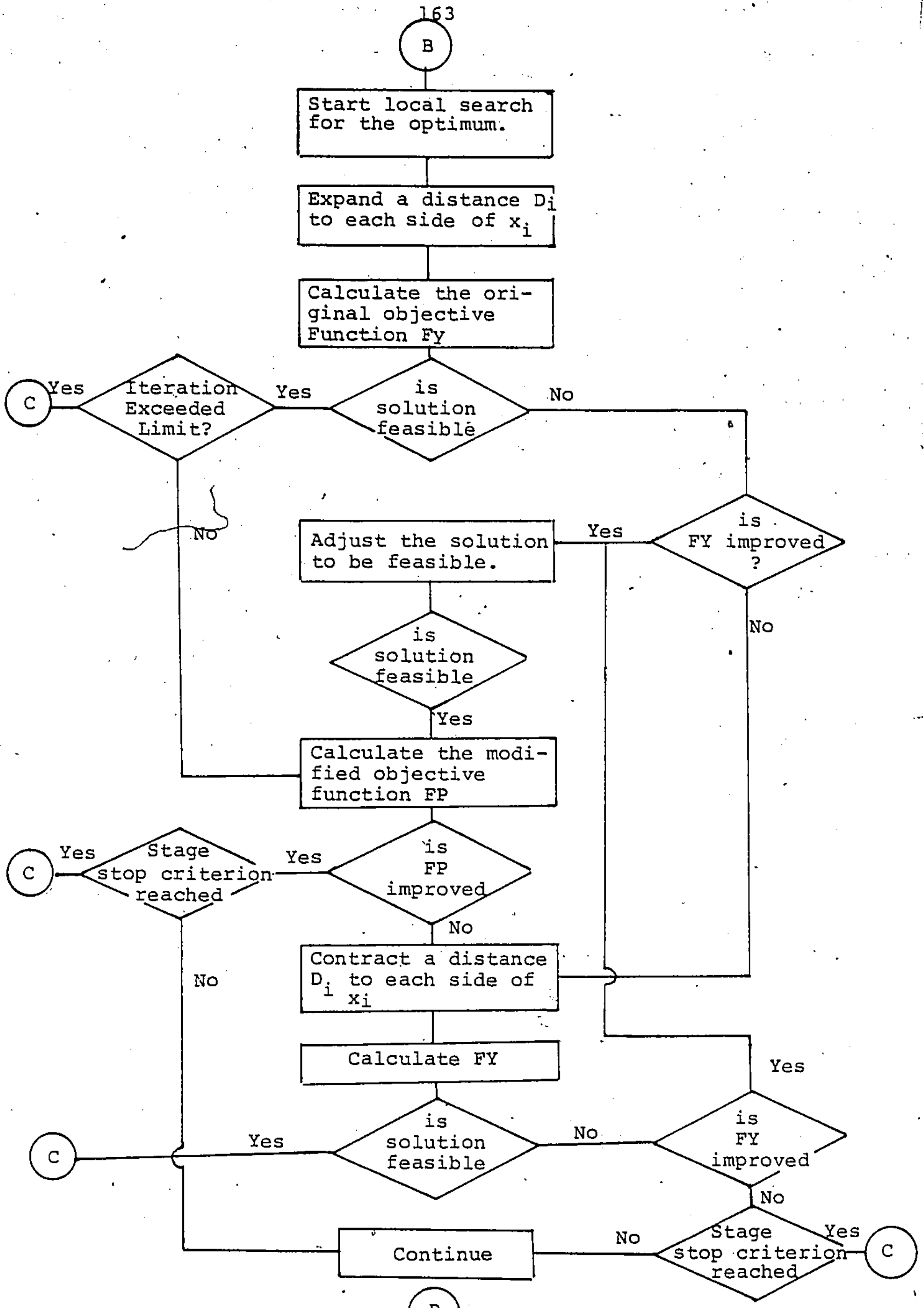
(3) SUBROUTINE OBRES which contains the objective function, F, and the problem constraints G(I).

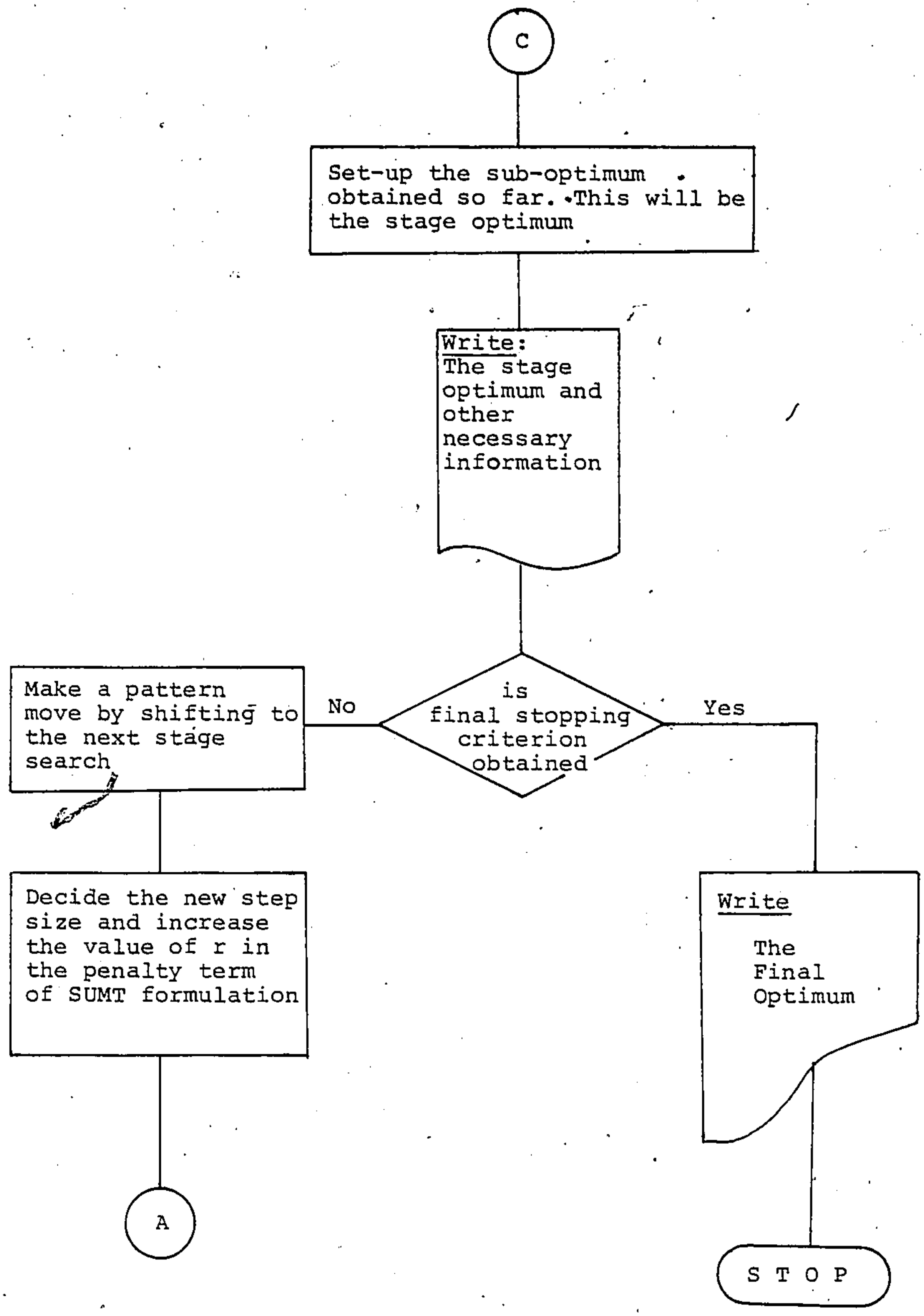
(4) SUBROUTINE NUMERIC which is developed to numerically compute the variations of the BOD concentration in each zone, the minimum level of DO concentration and its location in each zone, and the maximum concentration of phosphorus level in each zone.

(5) SUBROUTINE COST which is developed to calculate both the treatment and effluent charge costs for each pollution source at any zone. The output of this subroutine is directly supplied to the objective function, F, in SUBROUTINE OBRES. The following is the flow chart for the computer program used. The program listing follows the flow chart.

Computer Flow Chart




B
Start local search for the optimum.
Expand a distance D_i to each side of x_i
Calculate the original objective Function Fy
C
Yes
Iteration Exceeded Limit?
Yes
is solution feasible
No
No
Adjust the solution to be feasible.
Yes
is FY improved ?
No
is solution feasible
Yes
Calculate the modified objective function FP
C
Yes
Stage stop criterion reached
Yes
is FP improved
No
No
Contract a distance D_i to each side of x_i
Calculate FY
Yes
C
Yes
is solution feasible
No
is FY improved
No
Continue
No
Stage stop criterion reached
Yes
C


C
Set-up the sub-optimum obtained so far. This will be the stage optimum
Write:
The stage optimum and other necessary information
is final stopping criterion obtained
No
Yes
Make a pattern move by shifting to the next stage search
Decide the new step size and increase the value of r in the penalty term of SUMT formulation
A
Write
The Final Optimum
S T O P

```
FORTRAN IV G LEVEL  21                  MAIN                 DATE = 79170         03/10/17                 PAGE 0001
              IMPLICIT REAL*8(A-H,O-Z)
              DIMENSION X(50),FX(50),BX(50),PX(50),OX(50),PD(50),D(50),G(125),
             1FG(125),H(20),FH(20)
              COMMON /BLOGO/ NOITP,NOITB,B,D,ISKIP
              COMMON /BLOGY/ N,MG,MH,ITER,ITMAX,ICHECK,IB,LOST
              COMMON /BLOGG/ FG
              COMMON/BLOGR/ Q(10)
         1000 FORMAT(I5,5X,A2,A2,A2,3I5)
         1001 FORMAT(31X,1H*,A2,A2,A2,10H* PROBLEMS/
             130X,20(1H*)///25X,'NO. OF X(I)...',I4/25X,
             2'NO. OF G(J)...',I4/25X,'NO. OF H(K)...',
             3I4,///,' NO OF PROBLEMS ...',I4)
         1002 FORMAT (2D15.4,2I5,D15.4,3I5)
         1003 FORMAT (1H1,5X,7HPROBLEM ,I4/////)
         1004 FORMAT (I5,3D15.4)
         1005 FORMAT(20X,13HINITIAL POINT/5X,4HY = ,D11.4,7H,  P = ,D11.4,
             17H,  R = ,D11.4,11H,  RATIO = ,D11.4,2H, /5X,4HB = ,D11.4,
             211H,  INCUT = ,I4, 11H,  THETA = ,D11.4,2H .)
         1006 FORMAT(10X,2HX(,I3,4H) = ,D14.6,7H,     D(,I3,4H) = ,D14.6,2H .)
         1007 FORMAT(3X,75(1H*))
         1008 FORMAT(3X,15H**P OPTIMUM.. (,I4,1H)                /5X,5HFY = ,D13.6,6
             1H,FP = ,D13.6,7H,  R = ,D11.4,10H,  ITER = ,I5,1H,/5X,7HNOIT = ,I5
             2,9H,  NOB = ,I4,9H,  NOP = ,I4,10H,  NOBP = ,I4/5X,8HNOEXP = ,I4
             3,11H,  NOPAT = ,I4,11H,  NOCUT = ,I4,2H ./5X,8HYSTOP = ,D13.6,1H.)
         1011 FORMAT(5X/5X,16H**CONSTRAINTS ..)
         1012 FORMAT(10X,2HG(,I3,4H) = ,D14.6,2H .)
         1013 FORMAT(10X,2HH(,I3,4H) = ,D14.6,2H .)
         1015 FORMAT(3X,46H*****THE ABOVE RESULTS ARE THE FINAL OPTIMUM .)
         1016 FORMAT(3X,20H**NO. OF P OPTIMUM EXCEEDED ,I5,2H .)
         1020 FORMAT(5X//5X,47H**SELECTED FEASIBLE STARTING POINT..              )
         1021 FORMAT(    /////////////////////////5X)
         1022 FORMAT(1H ,5X,44H**THE PROBLEM MIGHT BE TOO FLAT. CHECK TIMES,I4,
             127H. R AND RATIO BE ADJUSTED. /7X,43HPROBABLY A DOUBLE PRECISION W
             2ILL BE NEEDED.)
        C*********************************************************************
              READ(5,1000) NOPM,NAME1,NAME2,NAME3,N,MG,MH
              WRITE(6,1021)
              WRITE(6,1001) NAME1,NAME2,NAME3,N,MG,MH,NOPM
              IOPM=1
        C*****READ IN ADITIONAL DATA
              CALL READIN (N,MG,MH)
        C*****READ IN INITIAL PARAMETERS AND STOPPING CRITERIA
            1 READ(5,1002) R,RATIO,ITMAX,INCUT,THETA,MAXP,ISIZE,ICUT
              WRITE(6,1003) IOPM
              WRITE(6,444) R,RATIO
          444 FORMAT (//,5X,'R    =',D15.4,'RATIO =',D15.4,//)
              MP=1
              MULT=1
              NOEXP=0
              NOPAT=0
              NOCUT=0
              NOR=1
              FNOR=NOR
              NOBP=0
              NOITP=0
              NOITB=0
              ITER=0
              NOIT=0
              LOST=0
              LLOST=0
              IB=0
              ICHECK=0
              B=0.0D0
              FN=N
              DO 4 I=1,N
              READ(5,1004) J,X(I),D(I),OX(I)
              IF(ISIZE) 3,3,2
            2 D(I)=OX(I)*0.02D0
            3 BX(I)=X(I)
              FX(I)=X(I)
              PD(I)=D(I)
              OX(I)=X(I)
            4 B=B+0.5D0*D(I)
        C*****DECIDE THE STARTING VALUE OF TOLERANCE LIMIT FOR G(J) .LT. 0.
              B=B/FN
              B=0.5D0*B
              PB=B
              CALL OBRES(FX,FY,FG,FH)
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FORTRAN IV G LEVEL  21                MAIN                DATE = 79[illegible]        03/10/17          PAGE 0002
 0064              CALL WEIGH(STGH,MG,FG,MH,FH)
 0065              ITER=0
 0066           11 CALL PENAT(FG,FH,PENA1,PENA2)
             C*****COMPUTE AN INITIAL VALUE OF R WHEN INPUT R VALUE IS .LE. 0.
 0067              IF(R) 12,12,13
 0068           12 R=DABS(FY/(PENA1+PENA2))
 0069              R=R/4.0D0
             C*****USE RATIO =4.0 WHEN INPUT RATIO VALUE IS .LE. 0.
 0070           13 IF(RATIO)14,14,15
 0071           14 RATIO=4.0D0
 0072           15 FP=FY+R*PENA1+R**(-0.5)*PENA2
 0073              WRITE(6,333) ITMAX,MAXP,ISIZE,ICUT
 0074          333 FORMAT(//, 5X,'ITMAX=',I5,5X,'MAXP=',I5,5X,'ISIZE=',I5,5X,'ICUT='
                  1,I5,//)
 0075              WRITE(6,1005) FY,FP,R,RATIO,B,INCUT,THETA
 0076              WRITE(6,1006) (I,FX(I),I,D(I),I=1,N)
 0077              WRITE(6,1007)
 0078              IF(LOST-2) 50,16,16
             C*****SELECT A EFASIBLE STARTING POINT WHEN INPUT INITIAL POINT IS NOT
             C     FLASIBLE SUBJECT TO INEQULITY CONSTRAINTS.
             C*****MAKE EXPLORATORY MOVE FOR SELECT A FEASIBLE STARTING POINT .
 0079           16 NOF=0
 0080              DO 28 I=1,N
 0081              FX(I)=X(I)+2.0D0*D(I)
 0082              CALL OBRES(FX,FY,FG,FH)
 0083              CALL WEIGH(TGH,MG,FG,MH,FH)
 0084              IF(LOST-2) 44,18,18
 0085           18 IF(STGH-TGH) 20,20,26
 0086           20 FX(I)=FX(I)-4.0D0*D(I)
 0087              CALL OBRES(FX,FY,FG,FH)
 0088              CALL WEIGH(TGH,MG,FG,MH,FH)
 0089              IF(LOST-2) 44,22,22
 0090           22 IF(STGH-TGH) 24,24,26
 0091           24 FX(I)=FX(I)+2.0D0*D(I)
 0092              NOF=NOF+1
 0093              GO TO 28
 0094           26 STGH=TGH
 0095              X(I)=FX(I)
 0096           28 CONTINUE
 0097              IF(NOF-N) 34,30,30
             C*****CUT STEP SIZE FOR SELECTING A FEASIBLE STARTING POINT ,
 0098           30 DO 32 I=1,N
 0099           32 D(I)=D(I)*0.5D0
 0100              GO TO 16
             C*****MAKE PATTERN MOVE FOR SELECTING A FASIBLE STARTING PCINY
 0101           34 DO 36 I=1,N
 0102           36 PX(I)=FX(I)+(FX(I)-DX(I))
 0103              CALL OBRES(PX,FY,FG,FH)
 0104              CALL WEIGH(TGH,MG,FG,MH,FH)
 0105              IF(STGH-TGH) 16,16,40
 0106           40 DO 42 I=1,N
 0107              X(I)=PX(I)
 0108           42 FX(I)=PX(I)
 0109              IF(LOST-2) 44,43,43
 0110           43 STGH=TGH
 0111              GO TO 16
 0112           44 DO 46 I=1,N
 0113              D(I)=PD(I)
 0114              OX(I)=FX(I)
 0115           46 DX(I)=FX(I)
 0116              LOST=3
 0117              WRITE(6,1020)
 0118              GO TO 11
 0119           48 DO 49 I=1,N
 0120           49 X(I)=FX(I)
 0121              LLOST=LOST
             C*****START TO MINIMIZE THE CURRENT P/ FUNCTION.
             C*****MAKE EXPLORATORY MOVE FOR MINIMIZING THE P- FUNCTION
 0122           50 IDIFF=0
 0123              MCUT=1
 0124           51 NOF=0
 0125              GO TO (52,102,52), MCUT
 0126           52 IDIFF=IDIFF+1
 0127              DO 101 I=1,N
 0128              X(I)=FX(I)+D(I)
 0129              LOST=0
 0130              CALL OBRES(X,Y,G,H)
 0131              IF(LOST-1) 62,62,53
```

```
      53 IF(Y-FY) 55,55,68
      55 CALL BACK(X,X,Y,G,H)
          NOITB=NOITB+1
         NOBP=NOBP+1
C*****CHECK THE ITMAX IS EXCEEDED OR NOT IN (BACK) .....LOST=1 MEANS
C        THE RETURNED POINT IS INFEASIBLE .
         IF(LOST-1)  56,150,56
      56 LOST=0
C*****CHECK THE ITMAX  IS EXCEEDED OR NOT IN (BACK) .....LOST=# .NE. 1
C        MEANS THE ENTERD POINT NEAR - FEASIBLE.
      62 IF(ICHECK-1) 64,140,140
      64 CALL PENAT(G,H,PENA1,PENA2)
         P=Y+R*PENA1+R**(-0.5)*PENA2
         IF(P-FP) 88,68,68
      68 X(I)=FX(I)-D(I)
         LOST=0
         CALL OBRES(X,Y,G,H)
         IF(LOST-1) 80,80,70
      70 IF(Y-FY) 73,73,86
      73 CALL BACK(X,X,Y,G,H)
         NOITB=NOITB+1
         NOBP=NOBP+1
C*****CHECK THEC  ITMAX IS EXCEEDED OR NOT IN (BACK) .....LOST =1 MEANS
C        THE ENTERED POINT IS NEAR FEASIBLE
         IF(LOST-1)  74,150,74
      74 LOST=0
      80 IF(ICHECK-1) 82,140,140
      82 CALL PENAT(G,H,PENA1,PENA2)
         P=Y+R*PENA1+R**(-0.5)*PENA2
         IF(P-FP) 88,86,86
      86 X(I)=FX(I)
         NOF=NOF+1
         GO  TO  99
      88 FY=Y
         FP=P
         NOITP=NOITP+1
         FX(I)=X(I)
         LLOST=LOST
         IF(MG) 94,94,90
      90 DO  92  JJ=1,MG
      92 FG(JJ)=G(JJ)
      94 IF(MH)99,99,96
      96 DO 98 KK=1,MH
      98 FH(KK)=H(KK)
C*****CHECK THE STAGE STOPPING CRITERION IS SATISFID OR NOT .
      99 IF(NOCUT-INCUT) 100,150,150
     100 IF(ICHECK-1) 101,150,101
     101 CONTINUE
         IF(NOF-N) 111,104,104
     102 DO 103 I=1,N
     103 X(I)=FX(I)+D(I)
         CALL OBRES(X,Y,G,H)
         IF(LOST-1) 1107,1107,1104
    1104 IF(Y-FY) 1105,1105,1108
    1105 CALL BACK(X,X,Y,G,H)
         NOITB=NOITB+1
         NOBP=NOBP+1
         IF(LOST-1) 1106,150,1106
    1106 LOST=0
         IF(ICHECK-1) 1107,140,140
    1107 CALL PENAT (G,H,PENA1,PENA2)
         P=Y+R*PENA1+R**(-0.5)*PENA2
         IF(P-FP) 1115,1108,1108
    1108 DO 1109 I=1,N
    1109 X(I)=FX(I)-D(I)
         CALL OBRES(X,Y,G,H)
         IF(LOST-1) 1113,1113,1110
    1110 IF(Y-FY) 1111,1111,1114
    1111 CALL BACK(X,X,Y,G,H)
         NOITB=NOITB+1
         NOBP=NOBP+1
         IF(LOST-1) 1112,150,1112
    1112 LOST=0
         IF(ICHECK-1) 1113,140,140
    1113 CALL PENAT(G,H,PENA1,PENA2)
         P=Y+R*PENA1+R**(-0.5)*PENA2
         IF(P-FP) 1115,1114,1114
    1114 NCUT=3
```

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```
      GO TO 51
 1115 FP=P
      FY=Y
      MCUT=1
      DO 1116 I=1,N
 1116 FX(I)=X(I)
      IF(MG) 1119,1119,1117
 1117 DO 1118 J=1,MG
 1118 FG(J)=G(J)
 1119 IF(MH) 50,50,1120
 1120 DO 1121 K=1,MH
 1121 FH(K)=H(K)
      GO TO 50
C*****CUT STEP SIZE FOR MINIMIZING THE P- FUNCTION..
  104 DO 105 I=1,N
  105 D(I)=0.5D0*D(I)
      NOCUT=NOCUT+1
      CALL PENAT(FG,FH,PENA1,PENA2)
      IF(IDIFF-INCUT) 51,106,106
  106 IF(MCUT-1) 107,107,110
  107 MCUT=2
  108 R=R/2.D0
      CALL PENAT (FG,FH,PENA1,PENA2)
      FP=FY+R*PENA1+R**(-0.5)*PENA2
      INCUT=INCUT+1
      NOCUT=0
      DO 109 I=1,N
      PD(I)=PD(I)*4.0D0
  109 D(I)=PD(I)
      WRITE(6,1022) MCUT
      IF(ISIZE) 2109,2109,51
 2109 DO 2110 I=1,N
 2110 D(I)=D(I)/FNOR
      GO TO 51
  110 IF(NOCUT-INCUT) 1114,150,150
  111 NOEXP=NOEXP+1
      MCUT=3
C*****MAKE PATTERN MOVE FOR MINIMIZING THE P- FUNCTION.
      DO 112 I=1,N
      PX(I)=FX(I)+(FX(I)-BX(I))
  112 BX(I)=FX(I)
      LOST=0
      CALL OBRES (PX,Y,G,H)
      IF(LOST-1) 124,124,113
  113 IF(Y-FY) 114,114,51
  114 CALL BACK(PX,X,Y,G,H)
      NOITB=NOITB+1
      NOBP=NOBP+1
C*****CHECK THE ITMAX EXCEEDED OR NOT IN (BACK) .....LOST=1 MEANS THE
C      RETURNED POINT IS INFEASIBLE .
      IF(LOST-1) 115,150,115
  115 LOST=0
C*****CHECK THE ITMAX IS EXCEEDED OR NOT IN (BACK) ......LOST.NE.1 MEANS
C      THE ENTERED POINT IS NEAR FEASIBLE.
  122 IF(ICHECK-1) 123,140,140
  123 IF(ISKIP-1) 124,48,48
  124 CALL PENAT(G,H,PENA1,PENA2)
      P=Y+R*PENA1+R**(-0.5)*PENA2
      IF(P-FP) 128,48,48
  128 NOPAT=NOPAT+1
      NOITP=NOITP+1
      DO 129 II=1,N
  129 FX(II)=PX(II)
      LLOST=LOST
  130 IF(MG) 133,133,131
  131 DO 132 J=1,MG
  132 FG(J)=G(J)
  133 IF(MH) 136,136,134
  134 DO 135 K=1,MH
  135 FH(K)=H(K)
  136 FY=Y
      FP=P
C*****CHECK THE STAGE STOPPING CRITERION IS SATISFIED OR NOT .
      IF(NOCUT-INCUT) 130,150,150
  138 IF(ICHECK-1) 50,150,150
C*****CHECK THE ITMAX EXCEEDED POINT (WHEN IT IS RETURNED FROM BACK)
C      IS BETTER OR NOT AND SET PROPER STAGE - OPTIMUM .
  140 CALL OBRES(X,Y,G,H)
```

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```
 0272               CALL PENAT(G,H,PENA1,PENA2)
 0273               P=Y+R*PENA1+R**(-0.5)*PENA2
 0274               IF(P-FP) 142,150,150
 0275           142 DO 144 I=1,N
 0276           144 FX(I)=X(I)
 0277               LLOST=LOST
 0278               GO TO 130
              C*****SET THE SUB OPTIMUM GOT BEFORE ENTERED TO BACK BE THE
              C     STAGE- OPTIMUM
 0279           150 NOPULL =0
 0280               PULL=0.63D0
 0281               IF(NG) 15,15,151
 0282           151 DO 152 J=1,MG
 0283               IF(FG(J)) 162,162,152
 0284           152 CONTINUE
              C*****CHECK THE STAGE OPTIMUM IS FEASIBLE OR NOT
 0285           160 IF(LLOST-1) 170,162,162
              C*****PULL BACK THE INFESIBLE STAGE-OPTIMUM INTO THE FEASIBLE REGION
 0286           162 DO 163 I=1,N
 0287           163 FX(I)=PULL*(FX(I)-UX(I))+CX(I)
 0288               NOPULL=NOPULL+1
 0289               CALL OBRES(FX,FY,FG,FH)
 0290               LLOST=LOST
 0291               NOITB=NOITB+1
 0292               IF(NOPULL-5) 160,164,164
 0293           164 NOPULL=0
 0294           165 DO 166 I=1,N
 0295           166 FX(I)=UX(I)
 0296               CALL OBRES(FX,FY,FG,FH)
 0297           170 LOST=0
 0298               CALL PENAT(FG,FH,PENA1,PENA2)
 0299               FP=FY+R*PENA1+R**(-0.5)*PENA2
 0300           200 NOIT=NOIT+ITER
 0301               YSTOP=DABS(FY/(FY-R*PENA1+R**(-0.5)*PENA2))
 0302               YSTOP=DABS(YSTOP-1.0D0)
 0303               CALL OBRES(FX,FY,FG,FH)
 0304               WRITE(6,1008)  NCR,FY,FP,R,ITER,NOIT,NOBP,NOITP,NOITB,NOEXP,
                   1NOPAT,NOCUT,YSTOP
 0305               WRITE(6,1006) (I,FX(I),I,D(I),I=1,N)
 0306               WRITE(6,1011)
 0307               IF(MG) 216,216,215
 0308           215 WRITE(6,1012) (J,FG(J),J=1,MG)
 0309           216 IF(MH) 218,218,217
 0310           217 WRITE(6,1013) (K,FH(K),K=1,MH)
 0311           218 CALL OUTPUT (N,MG,MH)
 0312               WRITE(6,1007)
              C*****CHECK THE FINAL STOPPING CRITERION IS SATISFIED OR NOT
 0313               IF(YSTOP-THETA) 230,230,220
              C*****CHECK THE ITMAX IS EXCEEDED OR NOT
 0314           220 IF(NOR-MAXP) 221,232,232
              C*****STOR LAST SUB-OPTIMUM
 0315           221 DO 222 I=1,N
 0316               D(I)=PD(I)
 0317           222 OX(I)=FX(I)
              C*****SHIFT TO THE NEXT STAGE SEARCH.
 0318               R=R/RATIO
 0319               FP=FY+R*PENA1+R**(-0.5)*PENA2
 0320               NOR=NOR+1
 0321               IF(NOR-5*MP)  224,224,223
 0322           223 INCUT=INCUT+1
 0323               MP=MP+1
 0324           224 IF(NOBP) 226,226,225
 0325           225 INCUT=INCUT+1
 0326           226 NOBP=0
 0327               MULT=1
 0328               NOITB=0
 0329               NOITP=0
 0330               ICHECK=0
 0331               NOEXP=0
 0332               NOPAT=0
 0333               NOCUT=0
 0334               ITER=0
 0335               ID=0
 0336               FNOR=NOR
 0337               B=0.0D0
 0338               MCUT=1
 0339               IDIFF=0
              C*****DECIDE THE INITIAL STEP-SIZE AND TOLERANCE LIMIT.
```

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```
FORTRAN IV G LEVEL  21                 MAIN                DATE = 79170        03/10/17            PAGE 0006

  0340              IF(ICUT) 229,229,227
  0341          227 DO 228 I=1,N
  0342              D(I)=PD(I)/FNUR
  0343          228 B=B+0.500*D(I)
  0344              B=B/FN
  0345              GO TO 50
  0346          229 B=PB
  0347              GO TO 50
  0348          230 WRITE(6,1015)
  0349              CALL  OUTPUT( N,MG,MH)
  0350              GO TO 234
  0351          232 WRITE(6,1016)  MAXP
  0352          234 IDPH=IDPH+1
  0353              IF(IDPH-NOPH) 1,1,236
  0354          236 STOP
  0355              END
```

```
FORTRAN IV G LEVEL  21                 MAIN                DATE = 79170        03/10/17

   *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
   *OPTIONS IN EFFECT*  NAME = MAIN     , LINECNT =       80
   *STATISTICS*    SOURCE STATEMENTS =       355,PROGRAM SIZE =     13726
   *STATISTICS*  NO DIAGNOSTICS GENERATED
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FORTRAN IV G LEVEL  21                  MAIN              DATE = 79170        03/10/17            PAGE 0001
                    C
                    C***********************************************************************
                    C
  0001                    SUBROUTINE WEIGH(TGH,NG,G,MH,H)
                    C     THIS SUBROUTINE COMPUTES THE TOTAL WEIGH OF VIOLATION
                    C     TO THE INEQUALITY CONSTRAINTS.
  0002                    IMPLICIT REAL*8(A-H,O-Z)
  0003                    DIMENSION G(125),H(20)
  0004                    TGH=0.0D0
  0005                    IF(NG) 4,4,1
  0006                  1 DO 3 IR =1,NG
  0007                    IF(G(IR)) 2,3,3
  0008                  2 TGH=TGH+G(IR)**2
  0009                  3 CONTINUE
  0010                  4 IF(MH) 8,8,5
  0011                  5 DO 7 IR=1,MH
  0012                    IF(H(IR)) 6,7,6
  0013                  6 TGH=TGH+H(IR)**2
  0014                  7 CONTINUE
  0015                  8 TGH=TGH**0.5D0
  0016                    RETURN
  0017                    END
```

```
FORTRAN IV G LEVEL  21                  WEIGH             DATE = 79170        03/10/17

 *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
 *OPTIONS IN EFFECT*  NAME = WEIGH    , LINECNT =       60
 *STATISTICS*     SOURCE STATEMENTS =        17,PROGRAM SIZE =       650
 *STATISTICS*  NO DIAGNOSTICS GENERATED
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FORTRAN IV G LEVEL  21                   MAIN              DATE = 79170        03/10/17            PAGE 0001

               C
               C*****************************************************************************
               C
 0001                SUBROUTINE PENAT(G,H,PENA1,PENA2)
               C     THIS SUBROUTINE COMPUTES THE PENALTY TERMS FOR SORT FORMULATION
 0002                IMPLICIT REAL*8(A-H,O-Z)
 0003                DIMENSION G(125),H(20)
 0004                COMMON /BLOGY/ N,NG,MH,ITER,ITMAX,ICHECK,IB,LLST
 0005                PENA1=0.0D0
 0006                PENA2=0.D0
 0007                IF(NG) 5,5,1
 0008              1 DO 4 I=1,NG
 0009                IF(G(I)) 4,2,4
               C     **SET G(I)=0.1E-46 WHEN G(I)=0 (ON THE BOUNDARY).
 0010              2 G(I)=0.10D-48
 0011              4 PENA1=PENA1+DABS(1.0D0/G(I))
 0012              5 IF(MH) 10,10,6
 0013              6 DO 9 K=1,MH
 0014              8 PENA2=PENA2+H(K)**2
 0015              9 CONTINUE
 0016             10 RETURN
 0017                END
```

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FORTRAN IV G LEVEL  21                   PENAT             DATE = 79170        03/10/17            PAGE 0002

  *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
  *OPTIONS IN EFFECT*  NAME = PENAT   , LINECNT =       80
  *STATISTICS*    SOURCE STATEMENTS =       17,PROGRAM SIZE =       618
  *STATISTICS*  NO DIAGNOSTICS GENERATED
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```
FORTRAN IV G LEVEL  21                  MAIN                DATE = 79170        03/10/17                    PAGE 0001
                C
                C*****************************************************************
                C
                      SUBROUTINE BACK(XB,X,Y,G,H)
                C     THIS SUBROUTINE PULS INFEASIBLE POINTS BACK INTO THE FEASIBLE
                C     OR NEAR FEASIBLE REGION.
                      IMPLICIT REAL*8(A-H,O-Z)
                      DIMENSION XB(50),X(50),G(125),H(20),D(50)
                      COMMON /BLOGY/ N,MG,MH,ITER,ITMAX,ICHECK,IB,LOST
                      COMMON /BLOGB/ NOITP,NOITB,B,D,ISKIP
                      ITERB=ITER
                      ISKIP=0
                      FRAC=0.50D0
                      CALL WEIGH(TGH,MG,G,MH,H)
                      IF(TGH) 8,8,4
                C     DECREAS E THE VALUE OF B IN RETURN
                    4 IF(B-TGH) 12,12,6
                    6 IF(0.70D0*B-TGH) 10,8,8
                    8 B=0.75D0*B
                   10 LOST=0
                      RETURN
                   12 FTGH=TGH
                C     MAKE EXPLORATORY MOVE FOR MINIMIZING TGH.
                   22 NOF=0
                      DO 38 NB=1,N
                      XB(NB)=XB(NB)-FRAC*D(NB)
                      CALL OBRES(XB,Y,G,H)
                      CALL WEIGH(TGH,MG,G,MH,H)
                      IF(LOST-2) 24,26,26
                   24 NOITP=NOITP+1
                   25 LOST=0
                      GO TO 46
                   26 NOITB=NOITB+1
                      IF(ICHECK-1) 27,45,45
                   27 IF(TGH-FTGH) 28,32,32
                   28 FTGH=TGH
                      IF(B-TGH) 38,38,28
                   32 XB(NB)=XB(NB)+D(NB)*2.0D0*FRAC
                      CALL OBRES(XB,Y,G,H)
                      CALL WEIGH(TGH,MG,G,MH,H)
                      IF(LOST-2) 24,34,34
                   34 NOITB=NOITB+1
                      IF(ICHECK-1) 35,45,45
                   35 IF(TGH-FTGH) 28,36,36
                   36 XB(NB)=XB(NB)-FRAC*D(NB)
                      NOF=NOF+1
                   38 CONTINUE
                      IF(NOF-N) 22,42,42
                C     ADD STEP SIZES FOR MINIMIZING TGH.
                   42 IF(ITER-ITERB-4*N) 44,43,59
                   43 FRAC=FRAC*5.0D0
                      GO TO 22
                   44 FRAC=FRAC*1.50D0
                      GO TO 22
                   45 LOST=1
                C     SET BASE POINT TO RETURN.
                   46 DO 50 NB=1,N
                      D(NB)=D(NB)*0.55D0
                   50 X(NB)=XB(NB)
                C     DECREASE THE VALUE OF B IN RETURN.
                      IF(0.70D0*B-TGH) 60,58,58
                   58 B=0.75D0*B
                      RETURN
                   59 LOST=0
                      ISKIP=1
                   60 RETURN
                      END

FORTRAN IV G LEVEL  21                  BACK                DATE = 79170        03/10/17

 *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
 *OPTIONS IN EFFECT*  NAME = BACK      , LINECNT =          80
 *STATISTICS*     SOURCE STATEMENTS =         57,PROGRAM SIZE =      1684
 *STATISTICS*  NO DIAGNOSTICS GENERATED
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```
FORTRAN IV G LEVEL  21                 MAIN               DATE = 79170         03/10/17         PAGE 0001

                C*******************************************************************
                C
 0001                   SUBROUTINE  COST
                C       THIS SUBROUTINE CALCULATE FOR EACH ZONE :
                C            (1) TOTAL TREATMENT COST FOR ALL SOURCES
                C            (2) CHARGE RATES FOR ALL SOURCES
                C            (3)TOTAL CHARGE COST FOR ALL SOURCES
                C
                C *******************************************************************
 0002                   IMPLICIT REAL*8(A-H,O-Z)
 0003                   COMMON/AREA 1/ F1,F2,PAY
 0004                   COMMON/FRISH/XT(10),XH(10),WBM(10),WPM(10),QF(10),JJ,PP
 0005                   COMMON/LIST/TC,XC,YC,TRC,CC,TCC,TTC,HR,IL
 0006                   DIMENSION  TRC(10),CC(10),XC(10),YC(10),HR(10)
                C     COST  FUNCTIONS
                C*******************
 0007                   CR(U,V,X1)=U*DEXP(-V*(1.0D0/(1.0D0-X1)))
 0008                   CHM(U,V,X1,W1)=U*DEXP(-V*(1.0D0/(1.0D0-X1)))*W1*(1.0D0-X1)*365.0D0
 0009                   SHC(Q,X1)=(Q/3785.0)*((1.20D0/(1.10D0**Q/3785.0D0))+1.0D0)*(165000
                      1.0D0*(0.71*X1-0.75*(X1**2)+0.24*(X1**5))+50000.0*X1**100)
 0010                   EHC(Q,W1,W2,X1,X2) =DEXP(10.1125D0)*(Q**0.3495D0)*((W1*X1)**
                      10.1778D0)*((W2*X2)**0.06852D0)
 0011                   PIC(Q1)=909.0D0+2273.0D0*(1.1/Q1)**0.5
 0012                   SIC(Q1)=2700.0D0+(2500.0D0/((Q1*365.0D0)**.670D0))+
                      1(1030.0D0*(0.020D0-0.0001*Q1))
 0013                   TIC(Q1)=1500.0D0+6450.0D0*((1.0D0/Q1)**0.630D0)
 0014                   TTC=0.0D0
 0015                   TCC=0.0D0
 0016                   DO 7 KL =1,JJ
 0017                   X1=XT(KL)
 0018                   W1=WBM(KL)
 0019                   GO  TO  (1,2) ,KL
 0020                 1 Q=QF(KL)
 0021                   U=XC(KL)
 0022                   V=YC(KL)
 0023                   X2=XH(KL)
 0024                   W2=WPA(KL)
 0025                   HR(KL)=CR(U,V,X1)
 0026                   TRC(KL)=EHC(Q,W1,W2,X1,X2)
 0027                   CC(KL)=CHM(U,V,X1,W1)
 0028                   TTC=TTC+TRC(KL)
 0029                   TCC=TCC+CC(KL)
 0030                   GO  TO  7
 0031                 2 Q1=QF(KL)
 0032                   V=YC(KL)
 0033                   U=XC(KL)
 0034                   HR(KL)=CR(U,V,X1)
 0035                   C=(W1*F2)/(Q1*F1)
 0036                   FAC=((F2/F1)*(W1/(C*Q1))*X1*365.0D0
 0037                   IF(X1.GE.0.0.AND.X1.LE.0.40)  GO  TO  4
 0038                   IF(X1.GE.0.40.AND.X1.LE.0.90)  GO  TO  5
 0039                   TRC(KL)=TIC(Q1)
 0040                   CC(KL)=CHM(U,V,X1,W1)
 0041                   HR(KL)=CR(U,V,X1)
 0042                   GO  TO  6
 0043                 4 TRC(KL)=PIC(Q1)
 0044                   CC(KL)=CHM(U,V,X1,W1)
 0045                   HR(KL)=CR(U,V,X1)
 0046                   GO  TO  6
 0047                 5 TRC(KL)=SIC(Q1)
 0048                   CC(KL)=CHM(U,V,X1,W1)
 0049                   HR(KL)=CR(U,V,X1)
 0050                 6 TRC(KL)=TRC(KL)*FAC
 0051                   TTC=TTC+TRC(KL)
 0052                   TCC=TCC+CC(KL)
 0053                 7 CONTINUE
 0054                   IL=JJ
 0055                   TC=TTC+TCC
 0056                   RETURN
 0057                   END

FORTRAN IV G LEVEL  21                 COST               DATE = 79170         03/10/17

   *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
   *OPTIONS IN EFFECT*  NAME = COST    , LINECNT =        60
   *STATISTICS*    SOURCE STATEMENTS =        57,PROGRAM SIZE =      2046
   *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
FORTRAN IV G LEVEL  21                 MAIN             DATE = 79170        03/10/17             PAGE 0001
              C*****************************************************************
 0001               SUBROUTINE NUMRIC(MINM,LD,PH,LO,CO,PO)
              C
              C     THIS  SUBROUTINE  CALCULATE THE CONCENTRATION LEVELS OF BOD,DO,AND
              C     PHOSPHORUS AT THE RIVER .THE CONCENTRATION FOR BOD AND DO ARE T
              C     CALCULATED THROUGH NUMERICAL INTEGRATION OF RUNG - KUTTA METHOD
              C
              C*****************************************************************
 0002               IMPLICIT REAL*8(A-H,O-Z)
 0003               COMMON/FNISH/AT(10),XH(10),AOH(10),APH(10),LF(10),JJ,NP
 0004               COMMON/AREA 1/ C1,C2,PAT
 0005               COMMON/AREA2/T1,ALPHI,OFF,DIMI,K3,LAI,NI
 0006               COMMON/AREA3/CHA(10),CHM(10),INC(10),QQD,QU,TIME,LS
 0007               DIMENSION BDOPF(200),DOPF(200),PHI(10)
 0008               REAL *8 BOD(500),DO(500),TIME(500)
 0009               REAL*8 LB,LD,MIN,MINM ,K3,LAI
 0010               UK1(T)=(2.3D0/(10.0D0)**2)*DEXP(0.0460D0*T)
 0011               RK2(T)=3.4300D0*DEXP(0.02500*(T-273.0D0))
 0012               CS(T)=4000.0D0*DEXP(-0.0210D0*T)
 0013               Z(T)=(ALPHI-PAT)/(PAT*(ALPHI-1.0D0))*(25.0D0-0.028D0*(T-303.0D0)
                   1**2)
 0014               BFUN(B,T)=-(UK1(T)+K3)*B+LAI
 0015               DFUN(B,C,T)=-UK1(T)*B+RK2(T)*(CS(T)-C)*Z(T)
 0016               DELT(X1,A1,GA)=F2*A1*(1.0D0-X1)/GA
 0017               DELT(X2,A2,GA)=F2*A2*(1.0D0-X2)/GA
 0018               BJ=0.0D0
 0019               SUF=0.0D0
 0020               SPH=0.0D0
 0021               DO 5 KL=1,JJ
 0022               X1=XH(KL)
 0023               A1=AOH(KL)
 0024             5 BJ=BJ+DELT(X1,A1,SOH1)
 0025               LB=BJ+LD
 0026               IF(NP.EQ.0)  GO  TO  7
 0027               DO  6  J=1,NP
 0028               GF=GF(J)*1.8500D0
 0029               X2=XH(J)
 0030               A2=PH(J)
 0031               PH(J)=DELT(X2,A2,GF)
 0032               SUF=SUF+GF(J)
 0033             6 SPH=SPH+PH(J)*GF(J)
 0034               PH=(SPH+PO*QA)/(SQF+QH)
 0035               GO  TO  8
 0036             7 PH=0.0D0
 0037             8 B=LB
 0038               C=CO
 0039               H=TIME/NI
 0040               TIME(1)=0.0D0
 0041               BOD(LS)=LB
 0042               DO(LS)=CO
 0043               MIN=CO
 0044             9 DO 10 I=2,NI
 0045               L=LS+I
 0046               TIME(L)=TIME(LS-1)+H
 0047               B1=H*BFUN(B,T1)
 0048               B2=H*BFUN(B+B1/2.0D0,T1)
 0049               B3=H*BFUN(B+B2/2.0D0,T1)
 0050               B4=H*BFUN(B+B3,T1)
 0051               DB=B1/6.0D0+B2/3.0D0+B3/3.0D0+B4/6.0D0
 0052               B=B+DB
 0053               BDOPF(I)=B
 0054               BOD(LS)=BDOPF(I)
 0055               D1=H*DFUN(B,C,T1)
 0056               D2=H*DFUN(B+B1/2.0D0,C+D1/2.0D0,T1)
 0057               D3=H*DFUN(B+B2/2.0D0,C+D2/2.0D0,T1)
 0058               D4=H*DFUN(B+B3/2.0D0,C+D3/2.0D0,T1)
 0059               D=(D1+D4)/6.0D0+(D2+D3)/3.0D0
 0060               C=C+D
 0061               DOPF(I)=C
 0062               DO(LS)=DOPF(I)
 0063               IF(DOPF(I).LE.0.0D0)  DOPF(I)=0.0D0
 0064               IF(DOPF(I).LT.MIN)  MIN=DOPF(I)
 0065            10 CONTINUE
 0066               MINM=MIN
 0067               CO=DOPF(I-1)
 0068               LO=BDOPF(I-1)
 0069               PO=PH
 0070               RETURN


FORTRAN IV G LEVEL  21                 NUMRIC           DATE = 79170        03/10/17             PAGE 0002
 0071               END


FORTRAN IV G LEVEL  21                 NUMRIC           DATE = 79170        03/10/17             PAGE 0003
  *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
  *OPTIONS IN EFFECT*  NAME = NUMRIC  , LINECNT =       60
  *STATISTICS*    SOURCE STATEMENTS =      71,PROGRAM SIZE =      4590
  *STATISTICS*  NO DIAGNOSTICS GENERATED
```

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Program Set-Up and Final Results for Example 1.

```
                            *SUMT   * PROBLEMS
                          ********************

                   NO. OF X(I)...   12
                   NO. OF G(J)...   27
                   NO. OF H(K)...    0

NO OF PROBLEMS ...    1
```

```
//SUMT    JOB  (XXXXXXXXXX,10,15,,8267),'MOUGY',CLASS=S                    JOB 417
//     .  EXEC       FORTGCLG,REGION=450K
//FORT.SYSIN  DD  *
IEF142I - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /FORT      / START 79170.0310
IEF374I STEP /FORT      / STOP  79170.0310 CPU   0MIN 13.46SEC MAIN 122K LCS   0K
IEF142I - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /LKED      / START 79170.0310
IEF374I STEP /LKED      / STOP  79170.0310 CPU   0MIN 00.99SEC MAIN 136K LCS   0K
//GO.SYSIN          DD       *
IEF142I - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /GO        / START 79170.0310
IEF374I STEP /GO        / STOP  79170.0316 CPU   3MIN 16.79SEC MAIN  66K LCS   0K
IEF375I  JOB /SUMT      / START 79170.0310
IEF376I  JOB /SUMT      / STOP  79170.0316 CPU   3MIN 31.24SEC
```

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```
FORTRAN IV G LEVEL  21                 MAIN              DATE = 79170          03/10/17                    PAGE 0001

               C ****************************************************************************
 0001                SUBROUTINE READIN(N,MG,MH)
               C ****************************************************************************
               C     THIS SUBROUTINE IS FOR READ IN ADDITIONAL DATA .
               C     USER SUPPLIES HIS OWN READ STATEMENT AND FORMAT .
               C     ARGUMENTS N,MG,MH ARE NUMBERS OF VARIABLES OF INEQUALITY CONSTRAIN
               C     AND OF EQUALITY CONSTRAINTS .
               C     COMMON/BLDGR/...... STATEMENT IS FOR TRANSFER DATA USE .
               C
 0002                IMPLICIT REAL*8(A-H,O-Z)
 0003                REAL *8  LO,LA,MGD
 0004                COMMON/AREA 1/ F1,F2,PAY
 0005                COMMON/TRNSF /ALPH(10),WB(10),WP(10),QR(10),T(10),TIM(10),LA(10)
                    1,MGD(10),AK3(10),MN(10),IN(10),NZ
 0006                COMMON/BLDGR/Q(10)
               C
               C****************************************************************************
               C
 0007                NZ=3
 0008                EPS=0.1000D00
 0009                PAY=0.3140D01
 0010                F1=1.0550D0
 0011                F2=0.1854D00
 0012                IN(1)=0
 0013                IN(2)=0
 0014                IN(3)=0
 0015                MN(1)=1
 0016                MN(2)=1
 0017                MN(3)=1
 0018                ALPH(1)=.3000D01
 0019                ALPH(2)=.3000D01
 0020                ALPH(3)=.3000D01
 0021                WB(1)=0.200D05
 0022                WB(2)=0.220D05
 0023                WB(3)=0.10D05
 0024                WP(1)=0.800D03
 0025                WP(2)=0.900D03
 0026                WP(3)=0.700D03
 0027                T(1)=290.0D0
 0028                T(2)=290.0D0
 0029                T(3)=290.0D0
 0030                TIM(1)=.10D01
 0031                TIM(2)=0.120D01
 0032                TIM(3)=0.150D01
 0033                AK3(1)=.1000D00
 0034                AK3(2)=.1000D00
 0035                AK3(3)=.1000D00
 0036                LA(1)=.2000D00
 0037                LA(2)=.2000D00
 0038                LA(3)=.2000D00
 0039                QR(1)=500.0D0
 0040                QR(2)=500.0D0
 0041                QR(3)=500.0D0
 0042                MGD(1)=2.5D0
 0043                MGD(2)=3.0D0
 0044                MGD(3)=2.0D0
 0045                RETURN
 0046                END

FORTRAN IV G LEVEL  21                 READIN            DATE = 79170          03/10/17

   *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
   *OPTIONS IN EFFECT*  NAME = READIN  , LINECNT =        80
   *STATISTICS*    SOURCE STATEMENTS =        46,PROGRAM SIZE =       820
   *STATISTICS*  NO DIAGNOSTICS GENERATED
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```
FORTRAN IV G LEVEL  21                 MAIN                 DATE = 79170        03/10/17              PAGE 0001

               C****************************************************************************
 0001                SUBROUTINE OUTPUT(N,MG,MH)
               C****************************************************************************
               C            THIS SUBROUTINE IS FOR USER TO PRINT OUT ADDITIONAL INFORMATION
               C         WANTED. ARGUMENTS N,MG,MH ARE NUMBERS OF VARIABLES , OF INEQUALIT
               C         -Y CONSTRAINTS , AND OF EQUALITY CONSTRAINTS .
               C            THE NEEDED DATA INFORMATION
               C            COMMON /BLOGO/..... IS FOR TRANSFER NEEDED DATA IN MAIN TO
               C         THE SUBROUTINE OUTPUT .
               C            USER SUPLLIES ALL NECESSARY FORMATS
               C****************************************************************************
 0002                IMPLICIT REAL*8(A-H,O-Z)
 0003                COMMON/AREA3/CHG(10),CHR(10),TMC(10),BOD,DO,TIME,LS
 0004                COMMON/BLOGO/G(125)
 0005                REAL *4 BOD(500),DO(500),TIME(500)
 0006                DO 10 I=1,3
 0007                WRITE(6,30)   CHR(I)
 0008             10 WRITE(6,20) I,CHG(I),I,TMC(I)
 0009             20 FORMAT(5X,'CHARGING COST (',I2,')=',D15.6,10X,'TREATMENT COST (',I
                    *2,')=',D15.6,/)
 0010             30 FORMAT(5X,'CHARGE  RATE  =',D15.6,/)
 0011                RETURN
 0012                END
```

```
FORTRAN IV G LEVEL  21                 OUTPUT               DATE = 79170        03/10/17              PAGE 0002

   *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
   *OPTIONS IN EFFECT*  NAME = OUTPUT  , LINECNT =       80
   *STATISTICS*     SOURCE STATEMENTS =        12,PROGRAM SIZE =       564
   *STATISTICS*  NO DIAGNOSTICS GENERATED
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```
FORTRAN IV G LEVEL  21                    MAIN                DATE = 79170          03/10/17              PAGE 0001

                C*******************************************************************
 0001                 SUBROUTINE OBRES(X,Y,G,H)
                C*******************************************************************
                C
                C     THIS SUBROUTINE COMPUTES OBJ. AND CONSTRAINT VALUES.
                C     USER SHOULD SUPPLY ALL NECESSARY STATEMENTS IN THE FORM ..
                C        Y=...... FUNCTION OF X(I) , FOR OBJECTIVE FUNCTION.
                C        G(J)=..... J FROM 1 TO MG , FOR CONSTRAINTS G(J).GT. 0.0 .
                C        H(K)=......K FROM 1 TO MH . FOR CONSTRAINTS H(K) .EQ.0.0 .
                C     INSERT THESE STATEMENTS IN THE BLOCK BELOW LINED BY*******
                C *******************************************************************
 0002                 IMPLICIT REAL*8(A-H,O-Z)
 0003                 DIMENSION X(50),G(125),H(20)
 0004                 DIMENSION  XC(10),YC(10),CC(10) ,HR(10),PHS(10),TRC(10)
 0005                 REAL *4 BOD(500),DO(500),TIME(500)
 0006                 REAL *8 MINDO(10),LU,LB,MIN,MINN,MAXBOD(10),K3,LA1 ,LA ,MGD
 0007                 COMMON/TRNSF /ALPH(10),WB(10),WP(10),QR(10),T(10),TIM(10),LA(10)
                     1,MGD(10),AK3(10),MN(10),IN(10),NZ
 0008                 COMMON/LIST/TC,XC,YC,TRC,CC,TCC,TTC,HR,IL
 0009                 COMMON/FRISH/XT(10),XH(10),WBM(10),WPM(10),QF(10),JJ,MM
 0010                 COMMON/AREA2/T1,ALPH1,QR1,TIM1,K3,LA1,NT
 0011                 COMMON/AREA3/CHG(10),CHR(10),TMC(10),BOD,DO,TIME,LS
 0012                 COMMON /BLOGY/ N,MG,MH,ITER,ITMAX,ICHECK,IB,LOST
 0013                 COMMON /BLOGR/ U(10)
 0014             100 FORMAT(3X,25H**THE ITERATION EXCEEDED ,I5,1H.)
                C
 0015                 SUM=0.0D0
 0016                 L1=1
 0017                 KU=0
 0018                 LS=1
 0019                 LU=5.0D0
 0020                 CU=6.0D0
 0021                 PU=0.050D0
 0022                 KK=1
 0023                 MX=0
 0024                 N1=0
 0025                 NC=0
 0026                 DO  9  J=1,NZ
 0027                 N1=N1+MN(J)+IN(J)
 0028                 NC=NC+2*MN(J)+IN(J)
 0029               9 CONTINUE
 0030                 NL=N1
 0031                 NC=NC+1
 0032                 DO 10 J=1,NZ
 0033                 JJ=MN(J)+IN(J)
 0034                 MM=MN(J)
 0035                 LL=IN(J)
 0036                 T1=T(J)
 0037              23 ALPH1=ALPH(J)
 0038                 TIM1=TIM(J)
 0039                 K3=AK3(J)
 0040                 LA1=LA(J)
 0041                 NT=TIM(J)*25.0
 0042                 QR1=QR(J)
 0043                 IF(MN(J).LE.0)  GO  TO  13
                C     ARRANGE  DATA  FOR  ORGANIC  WASTES  FROM  MUNICIPAL  SOURCES
 0044                 M2=MN(J)
 0045                 N2=IN(J)
 0046                 M1=MX+1
 0047                 MX1=MX+MN(J)
 0048                 K=1
 0049                 DO   11  L=M1,MX1
 0050                 XT(K)=X(L)
 0051                 WBM(K)=WB(L)
 0052                 WPM(K)=WP(L)
 0053                 QF(K)=MGD(L)
 0054                 K=K+1
 0055                 IF(K.GT.M2)  GO  TO  22
 0056              11 CONTINUE
                C     ARRANGE  DATA  FOR  PHOSPHORUS  WASTE  FROM  MUNICIPAL  SOURCES
 0057              22 NA=N1+1
 0058                 MA=MN(J)+N1
 0059                 M=1
 0060                 DO 12 I=NA,MA
 0061                 XH(M)=X(I)
 0062                 M=M+1
 0063                 IF(M.GT.M2)  GO  TO  33
 0064              12 CONTINUE
```

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```
0065          33 NI=NI+MN(J)
           C     ARRANGE  DATA  FOR  ORGANIC  WASTE  FROM  INDUSTRIAL  SURCES
0066          13 MX=MX+MN(J)
                 IF(IN(J).LE.0)  GO  TO  55
0068             MX1=MX+1
0069             MAX1=MX+IN(J)
0070             MNA=MN(J)+1
0071             MN1=MN(J)+IN(J)
0072             K=MNA
0073             DO  14  L=MX1,MAX1
0074             XI(K)=X(L)
0075             WOM(K)=WB(L)
0076             OF(K)=MGD(L)
0077             K=K+1
0078             IF(K.GT.MN1 )  GO  TO  44
0079          14 CONTINUE
           C     ARRANGE  DATTA  FOR  PHOSPHORUS  WASTE  FROM  INDUSTRIAL  SOURCES
0080          44 MX=MX+IN(J)
0081             IF (KK.EQ.1)  GO  TO  55
0082             NA=NI+1
0083             NA1=NI+IN(J)
0084             M=MNA
0085             DO  16  I=  NA,NA1
0086             XM(M)=X(I)
0087             WPM(M)=WP(I)
0088             M=M+1
0089             IF(M.GT.MN1 )  GO  TO  55
0090          16 CONTINUE
           C     CALCULATE THE CONCENTRATION LEVELS OF  BOD,DO,PO4 AND FIND
           C     THE MINIMUM POINT OF DO AT THE ZONE
0091          55 CALL NUMRIC (MINN,LB,PH,LO,CO,PO)
0092             MINDO(J)=MINN
0093             MAXBOD(J)=LB
0094             PHS(J)=PH
           C     ARRANGE  DATA  FOR  THE  COFFICINT'S  OF THE  CHARG
0095             DO  18  I=1,JJ
0096             XC(I)=X(NC)
0097             YC(I)=X(NL+NC)
0098             NC=NC+1
0099          18 CONTINUE
           C     CALCULATE ALL THE COST TERMS
0100             CALL  COST
0101             SUM=SUM+TC
0102             KU=KO+IL
0103             K=1
0104             DO  20  L=L1,KU
0105             CHR(L)=HR(K)
0106             CHG(L)=CC(K)
0107             TMC(L)=TRC(K)
0108             K=K+1
0109             IF(K.GT.IL )  GO  TO  77
0110          20 CONTINUE
0111          77 L1=L1+IL
0112          10 CONTINUE
           C     ************************************************************
           C     **NOTE.. STATEMENT NUMBERS 1,2,3,4,5,6,7,8,100 HVE BEEN USED
           C*****FUNCTION  DEFINITION
           C*****WRITE THE VALUES OF THE DECISION VARIABLES
           C*****THE WRITE STATEMENTS ARE DEACTIVATED BY PUTTING A'C' IN COLUMN 1.
           C*****IF THE OUTPUT OF THESE STATEMENTS ARE NEEDED, REMOVE THE 'C'.
           C        WRITE(6,1000) (X(I),I=1,6)
           C1000 FORMAT(' X(I)=',D15.7)
           C**    FUNCTION DEFINITION
           C**************************************************************
           C**    OBJ. FUNCTION.
           C**************************************************************
0113             Y=SUM
           C**************************************************************
           C**    EQUALITY CONSTRAINTS
           C*************************************************************
0114             G(1)=-MAXBOD(1)+15.0D0
0115             G(2)=-MAXBOD(2)+15.0D0
0116             G(3)=-MAXBOD(3)+15.0D0
0117             G(4)=MINDO(1)-5.0D0
0118             G(5)=MINDO(2)-5.0D0
0119             G(6)=MINDO(3)-5.0D0
0120             G(7)=-PHS(1)+0.1D0
0121             G(8)=-PHS(2)+0.1D0
```

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```
FORTRAN IV G LEVEL  21                OBRES              DATE = 79170        03/10/17              PAGE 0003

 0122                G(9)=-PHS(3)+0.10D0
 0123                G(10)=X(1)
 0124                G(11)=X(2)
 0125                G(12)=X(3)
 0126                G(13)=1.0D0-X(1)
 0127                G(14)=1.0D0-X(2)
 0128                G(15)=1.0D0-X(3)
 0129                G(16)=X(4)
 0130                G(17)=X(5)
 0131                G(18)=X(6)
 0132                G(19)=1.0D0-X(4)
 0133                G(20)=1.0D0-X(5)
 0134                G(21)=1.0D0-X(6)
 0135                G(22)=X(7)
 0136                G(23)=X(8)
 0137                G(24)=X(9)
 0138                G(25)=X(10)
 0139                G(26)=X(11)
 0140                G(27)=X(12)
 0141                LOST=0
 0142                ITER=ITER+1
 0143                IF(ITER-ITMAX) 3,1,2
            C*****OUTPUT THE MESSAGE OF ITMAX EXCEEDED.
 0144              1 WRITE(6,100) ITMAX
 0145              2 ICHECK=1
            C*****CHECK FOR THE VIOLATION TO INEQUALITY CONSTRAINTS.
 0146              3 IB=0
 0147                IF(NG) 8,8,4
 0148              4 DO 7 I=1,NG
 0149                IF(G(I)) 5,6,7
 0150              5 LOST=2
 0151                GO TO 7
 0152              6 IB=1
 0153              7 CONTINUE
 0154              8 RETURN
 0155                END
```

```
FORTRAN IV G LEVEL  21                OBRES              DATE = 79170        03/10/17

  *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
  *OPTIONS IN EFFECT*  NAME = OBRES    , LINECNT =       80
  *STATISTICS*    SOURCE STATEMENTS =       155,PROGRAM SIZE =      3100
  *STATISTICS*  NO DIAGNOSTICS GENERATED

  *STATISTICS*  NO DIAGNOSTICS THIS STEP


F88-LEVEL LINKAGE EDITOR OPTIONS SPECIFIED LET,LIST
          DEFAULT OPTION(S) USED -   SIZE=(133120,40960)
****MAIN        DOES NOT EXIST BUT HAS BEEN ADDED TO DATA SET
```

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```
********************************************************************************
**THE ITERATION EXCEEDED      50.
**P UPTIMUM.. (   13)
  FY =  0.122333D 07.FP =   0.122333D 07.  R =  0.2384D-03.  ITER =      52.
  NUIT =    658.  NOB =      0.  NUP =      6.  NUDP =     0
  NUEXP =      2.  NOPAT =      2.  NUCUT =      0 .
  YSTOP =   0.565116D-07.
         X(    1) =     0.580706D 00.       D(    1) =     0.769231D-03 .
         X(    2) =     0.680076D 00.       D(    2) =     0.769231D-03 .
         X(    3) =     0.780076D 00.       D(    3) =     0.769231D-03 .
         X(    4) =     0.809924D 00.       D(    4) =     0.769231D-03 .
         X(    5) =     0.989924D 00.       D(    5) =     0.769231D-03 .
         X(    6) =     0.909924D 00.       D(    6) =     0.769231D-03 .
         X(    7) =     0.139924D 00.       D(    7) =     0.769231D-03 .
         X(    8) =     0.139924D 00.       D(    8) =     0.769231D-03 .
         X(    9) =     0.139924D 00.       D(    9) =     0.769231D-03 .
         X(   10) =     0.280076D 00.       D(   10) =     0.769231D-03 .
         X(   11) =     0.306346D 00.       D(   11) =     0.769231D-03 .
         X(   12) =     0.325513D 00.       D(   12) =     0.769231D-03 .

 **CONSTRAINTS ..
         G(    1) =     0.689051D 01 .
         G(    2) =     0.586623D 01 .
         G(    3) =     0.719056D 01 .
         G(    4) =     0.756431D 00 .




         G(    5) =     0.449655D 00 .
         G(    6) =     0.405579D 00 .
         G(    7) =     0.327337D-01 .
         G(    8) =     0.313330D-01 .
         G(    9) =     0.190530D-01 .
         G(   10) =     0.500706D 00 .
         G(   11) =     0.680076D 00 .
         G(   12) =     0.780076D 00 .
         G(   13) =     0.419294D 00 .
         G(   14) =     0.319924D 00 .
         G(   15) =     0.219924D 00 .
         G(   16) =     0.889924D 00 .
         G(   17) -     0.989924D 00 .
         G(   18) =     0.909924D 00 .
         G(   19) =     0.110076D 00 .
         G(   20) =     0.100758D-01 .
         G(   21) =     0.900758D-01 .
         G(   22) =     0.139924D 00 .
         G(   23) =     0.139924D 00 .
         G(   24) =     0.139924D 00 .
         G(   25) =     0.280076D 00 .
         G(   26) =     0.306346D 00 .
         G(   27) =     0.325513D 00 .
  CHARGE   RATE   =     0.717460D-01

  CHARGING COST  ( 1)-     0.219604D 06            TREATMENT COST ( 1)=    0.281246D 06

  CHARGE   RATE   =     0.537070D-01

  CHARGING COST  ( 2)=     0.137973D 06            TREATMENT COST ( 2)=    0.318414D 06

  CHARGE   RATE   -     0.318484D-01

  CHARGING COST  ( 3)-     0.255655D 05            TREATMENT COST ( 3)=    0.240532D 06

********************************************************************************
*****THE ABOVE RESULTS ARE THE FINAL OPTIMUM .
```

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Program Set Up and Results for Example 2

```
                          *SORT   * PROBLEMS
                         ********************

                     NO. OF X(I)...   13
                     NO. OF G(J)...   35
                     NO. OF H(K)...    0

NO. OF PROBLEMS ...    1
```

```
//SORT     JOB  (XXXXXXXXXX,10,15,,8267),'HUJSY',CLASS=5                JOB 185
//        EXEC       FORTGCLG
//FORT.SYSIN      DD      *
IEF142I - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /FORT      / START 79197.1816
IEF374I STEP /FORT      / STOP  79197.1846 CPU    0MIN 14.27SEC MAIN  96K LCS    0K
IEF142I - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /LKED      / START 79197.1846
IEF374I STEP /LKED      / STOP  79197.1847 CPU    0MIN 01.03SEC MAIN 136K LCS    0K
//GO.SYSIN        DD    *
IEF142I - STEP WAS EXECUTED - COND CODE 0000
IEF373I STEP /GO        / START 79197.1847
IEF374I STEP /GO        / STOP  79197.1902 CPU    6MIN 34.95SEC MAIN  66K LCS    0K
IEF375I  JOB /SORT      / START 79197.1816
IEF376I  JOB /SORT      / STOP  79197.1902 CPU    6MIN 50.22SEC
```

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```
FORTRAN IV G LEVEL  21                  MAIN                                        PAGE 0001

                C ********************************************************************
 0001                 SUBROUTINE READIN(N,MG,MH)
                C ********************************************************************
                C     THIS SUBROUTINE IS FOR READ IN ADDITIONAL DATA .
                C     USER SUPPLIES HIS OWN READ STATEMENT AND FORMAT .
                C     ARGUMENTS N,MG,MH ARE NUMBERS OF VARIABLES OF INEQUALITY CONSTRAIN
                C     AND OF EQUALITY CONSTRAINTS .
                C     COMMON/BLOGR/...... STATEMENT IS FOR TRANSFER DATA USE . .
                C
 0002                 IMPLICIT REAL*8(A-H,O-Z)
 0003                 COMMON/BLOGR/D(10)
                C
 0004                 REAL*8 LO,LA,MGD
 0005                 COMMON/AREA 1/ F1,F2,PAY
 0006                 COMMON/TRNS/ ALPH(10),WH(10),WP(10),QR(10),T(10),TIM(10),LA(10)
                     1,MGD(10),AK3(10),MN(10),IN(10),NZ
                C********************************************************************
                C
 0007                 NZ=3
 0008                 EPS=0.1000D00
 0009                 PAY=0.3140D01
 0010                 F1=1.8550D0
 0011                 F2=0.1854D00
 0012                 IN(1)=1
 0013                 IN(2)=0
 0014                 IN(3)=1
 0015                 MN(1)=1
 0016                 MN(2)=1
 0017                 MN(3)=1
 0018                 ALPH(1)=.3000D01
 0019                 ALPH(2)=.3000D01
 0020                 ALPH(3)=.3000D01
 0021                 WH(1)=0.20D05
 0022                 WH(2)=0.10D05
 0023                 WH(3)=0.45D04
 0024                 WH(4)=0.75D04
 0025                 WH(5)=0.30D05
 0026                 WP(1)=700.0D0
 0027                 WP(2)=0.0D0
 0028                 WP(3)=600.0D0
 0029                 WP(4)=650.0D0
 0030                 WP(5)=0.0D0
 0031                 T(1)=0.290D03
 0032                 T(2)=.2250D03
 0033                 T(3)=0.3000D03
 0034                 TIM(1)=0.2500D01
 0035                 TIM(2)=0.20D01
 0036                 TIM(3)=0.300D01
 0037                 AK3(1)=.1000D00
 0038                 AK3(2)=.1000D00
 0039                 AK3(3)=.1000D00
 0040                 LA(1)=.2000D00
 0041                 LA(2)=.2000D00
 0042                 LA(3)=.2000D00
 0043                 QR(1)=500.0D0
 0044                 QR(2)=500.0D0
 0045                 QR(3)=500.0D0
 0046                 MGD(1)=10.0D0
 0047                 MGD(2)=6.0D0
 0048                 MGD(3)=3.0D0
 0049                 MGD(4)=4.0D0
 0050                 MGD(5)=8.0D0
 0051                 RETURN
 0052                 END
```

```
FORTRAN IV G LEVEL  21                MAIN                DATE = 79165        01/14/30                PAGE 0001

                C*********************************************************************
 0001                 SUBROUTINE OUTPUT(N,MG,MH)
                C*********************************************************************
                C            THIS SUBROUTINE IS FOR USE TO PRINT OUT ADDITIONAL INFORMATION
                C       WANTED. ARGUMENTS N,MG,MH ARE NUMBERS OF VARIABLES , OF INEQUALIT
                C       -Y CONSTRAINTS , AND OF EQUALITY CONSTRAINTS .
                C            THE NEEDED DATA INFORMATION
                C            COMMON /BLOCO/..... IS FOR TRANSFER NEEDED DATA IN MAIN TO
                C       THE SUBROUTINE OUTPUT .
                C       .    USER SUPPLIES ALL NECESSARY FORMATS
                C*********************************************************************
 0002                 IMPLICIT REAL*8(A-H,O-Z)
 0003                 COMMON/AREA3/CHG(10),CHR(10),TMC(10),BOD,OD,TIME,ES
 0004                 COMMON/BLOCO/G(125)
 0005                 REAL *4 BOD(500),OD(500),TIME(500)
 0006                 DO 10 I=1,5
 0007                 WRITE(6,30)    CHR(I)
 0008              10 WRITE(6,20) I,CHG(I),I,TMC(I)
 0009              20 FORMAT(5X,'CHARGING COST (',I2,')=',D15.6,10X,'TREATMENT COST (',I
                     *2,')=',D15.6,/)
 0010              30 FORMAT(5X,'CHARGE  RATE  =',D15.6,/)
 0011                 RETURN
 0012                 END
```

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```
FORTRAN IV G LEVEL  21                MAIN                DATE = 79170         03/10/17             PAGE 0001

               C*********************************************************************
 0001                SUBROUTINE OBRES(X,Y,G,H)
               C*********************************************************************
               C
               C     THIS SUBROUTINE COMPUTES OBJ. AND CONSTRAINT VALUES.
               C     USER SHOULD SUPPLY ALL NECESSARY STATEMENTS IN THE FORM ..
               C        Y=..... FUNCTION OF X(I) , FOR OBJECTIVE FUNCTION.
               C          G(J)=..... J FROM 1 TO MG , FOR CONSTRAINTS G(J).GT. 0.0 .
               C          H(K)=......K FROM 1 TO MI , FOR CONSTRAINTS H(K) .EQ.0.0 .
               C     INSERT THESE STATEMENTS IN THE BLOCK BELOW LINED BY*******
               C *********************************************************************
 0002                IMPLICIT REAL*8(A-H,O-Z)
 0003                DIMENSION X(50),G(125),H(20)
 0004                DIMENSION  XC(10),YC(10),CC(10) ,HR(10),PHS(10),TRC(10)
 0005                REAL *4 BUD(500),DD(500),TIME(500)
 0006                REAL *8 MINBD(10),LU,LB,MIN,MINN,MAXBUD(10),KJ,LAI ,LA ,MGD
 0007                COMMON/TRNSF /ALPH(10),WB(10),WP(10),QR(10),T(10),TIM(10),LA(10)
                    1,MGD(10),AKJ(10),MN(10),IN(10),NZ
 0008                COMMON/LIST/TC,XC,YC,TRC,CC,TCC,TTC,HR,IL
 0009                COMMON/FNISH/XT(10),XH(10),WBM(10),WPM(10),OF(10),JJ,MM
 0010                COMMON/AREA2/TI,ALPHI,QRI,TIM1,K3,LAI,NT
 0011                COMMON/AREA3/CMG(10),CMP(10),TMC(10),BUD,DB,TIME,LS
 0012                COMMON /BLOGY/ N,MG,MI,ITER,ITMAX,ICHECK,IB,LOST
 0013                COMMON /BLOGR/ U(10)
 0014            100 FORMAT(3X,25H**THE ITERATION EXCEEDED ,I5,1H.)
               C
 0015                SUM=0.0D0
 0016                LI=1
 0017                KU=0
 0018                LS=1
 0019                LU=5.0D0
 0020                CU=6.0D0
 0021                PU=0.05D00
 0022                KK=1
 0023                MX=0
 0024                NI=0
 0025                NC=0
 0026                DO  9  J=1,NZ
 0027                NI=NI+MN(J)+IN(J)
 0028                NC=NC+2*MN(J)+IN(J)
 0029              9 CONTINUE
 0030                ML=NI
 0031                NC=NC+1
 0032                DO 10 J=1,NZ
 0033                JJ=MN(J)+IN(J)
 0034                MM=MN(J)
 0035                LL=IN(J)
 0036                TI=T(J)
 0037             23 ALPHI=ALPH(J)
 0038                TIM1=TIM(J)
 0039                K3=AK3(J)
 0040                LAI=LA(J)
 0041                NT=TIM(J)*25.0
 0042                QRI=QR(J)
 0043                IF(MN(J).LE.0)  GO  TO  13
               C    ARRANGE  DATA  FOR  ORGANIC  WASTES  FROM  MUNICIPAL  SOURCES
 0044                M2=MN(J)
 0045                N2=IN(J)
 0046                M1=MX+1
 0047                MX1=MX+MN(J)
 0048                K=1
 0049                DO  11  L=M1,MX1
 0050                XT(K)=X(L)
 0051                WBM(K)=WB(L)
 0052                WPM(K)=WP(L)
 0053                OF(K)=MGD(L)
 0054                K=K+1
 0055                IF(K.GT.M2)  GO  TO  22
 0056             11 CONTINUE
               C    ARRANGE  DATA  FOR  PHOSPHORUS  WASTE  FROM  MUNICIPAL  SOURCES
 0057             22 NA=NI+1
 0058                MA=MN(J)+NI
 0059                M=1
 0060                DO 12 I=NA,MA
 0061                XH(M)=X(I)
 0062                M=M+1
 0063                IF(M.GT.M2)  GO  TO  33
 0064             12 CONTINUE
```

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```
      33 NI=NI+MN(J)
C        ARRANGE  DATA  FOR  ORGANIC  WASTE  FROM  INDUSTRIAL  SURCES
      13 MX=MX+MN(J)
         IF(IN(J).LE.0)  GO  TO  55
         MX1=MX+1
         MAX1=MX+IN(J)
         MNA=MN(J)+1
         MN1=MN(J)+IN(J)
         K=MNA
         DO  14  L=MX1,MAX1
         XI(K)=X(L)
         WIM(K)=WB(L)
         QF(K)=MGD(L)
         K=K+1
         IF(K.GT.MN1 )  GO  TO  44
      14 CONTINUE
C        ARRANGE  DATTA  FOR  PHOSPHORUS  WASTE  FROM  INDUSTRIAL  SOURCES
      44 MX=MX+IN(J)
         IF (KK.EQ.1)  GO  TO  55
         NA=NI+1
         NA1=NI+IN(J)
         M=MNA
         DO  16  I=  NA,NA1
         XH(M)=X(I)
         WPM(M)=WP(I)
         M=M+1
         IF(M.GT.MN1 )  GO  TO  55
      16 CONTINUE
C        CALCULATE THE CONCENTRATION LEVELS OF BOD,DO,PO4 AND FIND.
C        THE MINIMUM POINT OF DO AT THE ZONE
      55 CALL NUMRIC (MINM,LB,PM,LU,CU,PU)
         MINDO(J)=MINM
         MAXBOD(J)=LB
         PHS(J)=PM
C        ARRANGE  DATA  FOR  THE  COFFICINT'S  OF THE  CHARG
         DO  18  I=1,JJ
         XC(I)=X(NC)
         YC(I)=X(NL+NC)
         NC=NC+1
      18 CONTINUE
C        CALCULATE ALL THE COST TERMS
         CALL  COST
         SUM=SUM+TC
         KO=KO+IL
         K=1
         DO  20  L=L1,KO
         CHR(L)=HR(K)
         CHG(L)=CC(K)
         TAC(L)=TRC(K)
         K=K+1
         IF(K.GT.IL )  GO  TO  77
      20 CONTINUE
      77 L1=L1+IL
      10 CONTINUE
C     ****************************************************************
C      **NOTE.. STATEMENT NUMBERS 1,2,3,4,5,6,7,8,100 HVE BEEN USED
C****FUNCTION  DEFINITION
C*****WRITE THE VALUES OF THE DECISION VARIABLES
C*****THE WRITE STATEMENTS ARE DEACTIVATED BY PUTTING A'C' IN COLUMN 1.
C******IF THE OUTPUT OF THESE STATEMENTS ARE NEEDEC, REMOVE THE 'C'.
C        WRITE(6,1000) (X(I),I=1,6)
C1000 FORMAT('  X(I)=',6D15.7)
C**      FUNCTION DEFINITION
C*******************************************************************
C**      OBJ. FUNCTION.
C*******************************************************************
         Y=SUM
C*******************************************************************
C**      EQUALITY CONSTRAINTS
C******************************************************************
         G(1)=-MAXBOD(1)+15.0D0
         G(2)=-MAXBOD(2)+12.0D0
         G(3)=-MAXBOD(3)+15.0D0
         G(4)=MINDO(1)-4.5D0
         G(5)=MINDO(2)-5.0D0
         G(6)=MINDO(3)-4.0D0
         G(7)=-PHS(1)+0.1D00
         G(8)=-PHS(2)+0.1D00
```

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```
FORTRAN IV G LEVEL  21              [illegible]          DATE = 79165         01/14/30           PAGE 0003
  0122                   G(9)=-PHS(3)+0.1D00
  0123                   G(10)=X(1)
  0124                   G(11)=X(2)
  0125                   G(12)=X(3)
  0126                   G(13)=X(4)
  0127                   G(14)=X(5)
  0128                   G(15)=1.0D0-X(1)
  0129                   G(16)=1.0D0-X(2)
  0130                   G(17)=1.0D0-X(3)
  0131                   G(18)=1.0D0-X(4)
  0132                   G(19)=1.0D0-X(5)
  0133                   G(20)=X(6)
  0134                   G(21)=X(7)
  0135                   G(22)=X(8)
  0136                   G(23)=1.0D0-X(6)
  0137                   G(24)=1.0D0-X(7)
  0138                   G(25)=1.0D0-X(8)
  0139                   G(26)=X(9)
  0140                   G(27)=X(10)
  0141                   G(28)=X(11)
  0142                   G(29)=X(12)
  0143                   G(30)=X(13)
  0144                   G(31)=X(14)
  0145                   G(32)=X(15)
  0146                   G(33)=X(16)
  0147                   G(34)=X(17)
  0148                   G(35)=X(18)
  0149                   LOST=0
  0150                   ITER=ITER+1
  0151                   IF(ITER-ITMAX) 3,1,2
               C*****OUTPUT THE MESSAGE OF ITMAX EXCEEDED.
  0152                 1 WRITE(6,100) ITMAX
  0153                 2 ICHECK=1
               C*****CHECK FOR THE VIOLATION TO INEQUALITY CONSTRAINTS.
  0154                 3 IB=0
  0155                   IF(NG) 8,8,4
  0156                 4 DO 7 I=1,NG
  0157                   IF(G(I)) 5,6,7
  0158                 5 LOST[illegible]
  0159                   GO TO 7
  0160                 6 IB=1
  0161                 7 CONTINUE
  0162                 8 RETURN
  0163                   END
```

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```
***OPTIMUM.. (  12)
  FY =  0.2685790 07,FP =   0.2685790 07,  R =  0.9537D-03,  ITER =     52,
  NUIT =     608,  NSB =     0,  ISP =     2,  NOOP =    3
  NOEXP =      1,  NSPAT =     1,  NDCU =      0
  YSTOP =   0.957022D-07,
        X(   1) =      0.777769D 00.      D(   1) =    0.333333D-04 .
        X(   2) =      0.642811D 00.      D(   2) =    0.133333D-04 .
        X(   3) =      0.607689D 00.      D(   3) =    0.133333D-04 .
        X(   4) =      0.627659D 00.      D(   4) =    0.433333D-04 .
        X(   5) =      0.427689D 00.      D(   5) =    0.133333D-04 .
        X(   6) =      0.856060D 00.      D(   6) =    0.133333D-03 .
        X(   7) =      0.056060D 00.      D(   7) =    0.433333D-03 .
        X(   8) =      0.720606D 00.      D(   8) =    0.433333D-03 .
        X(   9) =      0.940606D-01.      D(   9) =    0.333333D-04 .
        X(  10) =      0.240610D 00.      D(  10) =    0.333333D-04 .
        X(  11) =      0.805606D-01.      D(  11) =    0.433333D-04 .
        X(  12) =      0.144061D 00.      D(  12) =    0.333333D-04 .
        X(  13) =      0.245061D 00.      D(  13) =    0.433333D-04 .
        X(  14) =      0.254939D 00.      D(  14) =    0.433333D-04 .
        X(  15) =      0.454939D 00.      D(  15) =    0.433333D-04 .
        X(  16) =      0.134939D 00.      D(  16) =    0.333333D-04 .
        X(  17) =      0.121939D 00.      D(  17) =    0.433333D-04 .
        X(  18) =      0.362606D 00.      D(  18) =    0.433333D-04 .

   **CONSTRAINTS ..
        G(   1) =      0.702763D 01 .
        G(   2) =      0.778963D 01 .
        G(   3) =      0.886112D 01 .
        G(   4) =      0.127128D 01 .
        G(   5) =      0.732931D 00 .
        G(   6) =      0.963622D 00 .
        G(   7) =      0.193958D-01 .
        G(   8) =      0.380563D-01 .
        G(   9) =      0.283142D-01 .
        G(  10) =      0.777769D 00 .
        G(  11) =      0.642811D 00 .
        G(  12) =      0.607689D 00 .
        G(  13) =      0.627689D 00 .
        G(  14) =      0.427689D 00 .
        G(  15) =      0.322211D 00 .
        G(  16) =      0.357169D 00 .
        G(  17) =      0.392311D 00 .
        G(  18) =      0.372311D 00 .
        G(  19) =      0.172311D 00 .
        G(  20) =      0.905606D 00 .
        G(  21) =      0.705606D 00 .
        G(  22) =      0.220606D 00 .
        G(  23) =      0.143939D-01 .
        G(  24) =      0.943939D-01 .
        G(  25) =      0.793939D-01 .
        G(  26) =      0.940606D-01 .
        G(  27) =      0.324061D 00 .
        G(  28) =      0.805606D-01 .
        G(  29) =      0.141061D 00 .
        G(  30) =      0.243061D 00 .
        G(  31) =      0.254939D 00 .
        G(  32) =      0.549390D 00 .
        G(  33) =      0.134939D 00 .
        G(  34) =      0.121939D 00 .
        G(  35) =      0.362606D 00 .
   CHARGE   RATE   =  0.29863950D-01

   CHARGING COST  (  1)= 0.48443431D 05            TREATMENT COST  ( 1)= 0.47988572D 06

   CHARGE   RATE   = 0.29589280D-01

   CHARGING COST  (  2)= 0.38576766D 05            TREATMENT COST  ( 2)= 0.65143174D 06

   CHARGE   RATE   = 0.12334857D-01



   CHARGING COST  (  3)= 0.27665941D 05            TREATMENT COST  ( 3)= 0.22753333D 06

   CHARGE   RATE   = 0.60747480D-01

   CHARGING COST  (  4)= 0.61839721D 05            TREATMENT COST  ( 4)= 0.27895040D 06

   CHARGE   RATE   = 0.94762550D-01

   CHARGING COST  (  5)= 0.56374306D 05            TREATMENT COST  ( 5)= 0.82508027D 06
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*****THE ABOVE RESULTS ARE THE FINAL OPTIMUM
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VITA AUCTORIS

1946	Born on December 23rd, Mansoura, Egypt.
1968	Graduated from Cairo University, Egypt with Bachelor Degree of Science in Mechanical Engineering.
1968	Worked as Production Engineer at the Imperial British Tobacco Company, Giza, Egypt.
1974	Received Diploma in Mathematical Statistics from Cairo University, Egypt.
1975	Completed Degree of Master of Science in Production Engineering from Cairo University, Egypt.
1976	Held a teaching and research assistantship at the University of Windsor, Ontario.
1978	Employed as an Industrial Engineer, with Pyramid Homes Company, Windsor, Ontario.
1979	Candidate for Master of Applied Science Degree in Industrial Engineering.