A STUDY OF THE OPTIMUM NUMBER, SIZES, AND LOCATIONS OF WASTEWATER TREATMENT FACILITIES IN ALACHUA COUNTY, FLORIDA

BY
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A DISSERTATION PRESENTED TO THE GRADUATE COUNCIL OF
THE UNIVERSITY OF FLORIDA
IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE
DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA
1975

ACKNOWLEDGMENT

My graduate study has been rewarding and enjoyable. Many people are responsible and to them I feel a debt of gratitude.

My greatest debt is to Max Langham, Chairman of my Supervisory Committee, who has provided academic and technical guidance as well as criticism in a masterful way, making the preparation of this dissertation both exciting and enjoyable. More than this, he has provided a warm friendship in trying times. Bobby Eddleman, Frederick Goddard, and Lloyd B. Baldwin critically reviewed the manuscript. Special thanks also go to LeAnne VanElburg and Janet Eldred for their help in typing the preliminary drafts.

Leo Polopolus, the faculty, and my fellow graduate students of the Department of Food and Resource Economics have contributed greatly to making this study period significant. My friends on this campus have done likewise. To all I am grateful.

This study could not have been accomplished without the financial support of the Center for Community and Rural Development and the Florida Agricultural Experiment Stations.

To the many unmentioned others, I am grateful.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF FIGURES

Abstract of Dissertation Presented to the Graduate Council of the University of Florida in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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June, 1975

Chairman: Max R. Langham
Major Department: Food and Resource Economics

Economies of scale provide the main incentive for regionalization of wastewater treatment facilities. The cost of collecting wastewater increases with the size of plant and serves to offset within plant scale economies. Two types of secondary treatment and three tertiary treatment processes were considered as feasible alternatives. They were high-rate trickling filter system, activated sludge system, and two clarifier lime clarification processes, lime recalcination, and ammonia stripping process, respectively.

The space and time dimensions of regionalization were considered. In order to find the potential sites of regional treatment plants, a cost minimization model was used. For the consolidation over time an exponential objective function was minimized subject to discrete capacity requirements.

Estimates of construction and operation and maintenance costs were based upon Environmental Protection Agency (EPA) studies. The rates of

cost increases over time were also estimated from EPA cost indexes as .12, .10, and .07 per year for force main construction cost, pumping station and sewage treatment plant construction costs, and operation and maintenance costs for both force mains and sewage treatment plants, respectively. Service lives for pumping station and wastewater treatment were taken as 25 years, and for pipelines as 50 years. An interest rate of 5% per year was assumed.

A least cost staging policy to satisfy the wastewater treatment requirements of the nine cities in Alachua County, Florida for the years 1975, 1980, and 1990 was determined with the model. The results were sensitive to the required quality of secondary effluents.

If the required quality of secondary effluent is set at above 80% removal, activated sludge plants will be required to provide the least cost method of treating wastewater. The results show that secondary treatment cost will be minimized if High Springs, Alachua, Archer, and Newberry cooperate to build a regional treatment plant in 1975 to satisfy their 1980 demands, and then construct individual plants in 1990 to satisfy the additional demands at that time. The other cities would satisfy their demands by building individual activated sludge plants in 1975 to satisfy their 1980 demands with additions being made in 1990. The minimum tertiary treatment cost combination would require the construction of two regional treatment plants, one for High Springs, Alachua, Archer, and Newberry, and one for Waldo and Hawthorne, in 1975 to satisfy the 1980 demands of these six cities. Their additional demands in 1990 would be met with plants added in each city. Gainesville, LaCrosse, and Micanopy would satisfy their tertiary treatment demands with individual plants constructed in 1975 with additions in 1990.

If the required quality of secondary effluent is set at 80% removal, the results show that secondary treatment cost for the county will be minimized if each city builds a trickling filter plant which satisfies 1980's wastewater treatment demands in 1975 with additions to capacity being made in 1990. The minimum tertiary treatment cost combination suggests that there will be regionalization of treatment in 1975 to satisfy the 1980's demands of three cities--Newberry, Archer, and Alachua. Additional demands in 1990 were satisfied by building individual treatment plants in these three cities. The other six cities would satisfy their tertiary treatment with individual plants constructed on the same schedule as the trickling filter plants.

The possibility of substituting land spreading for tertiary treatment is discussed, and the factors which should be considered in land treatment are analyzed with the aid of an optimization model. The break-even distances of transmission pipelines for land treatment as a substitute for tertiary treatment are calculated and presented.

CHAPTER I
INTRODUCTION

The Problem and Objectives

The environmental thrust of the 1970's has resulted in regulations to clean up wastewater from a number of sources including industry, municipalities, and nuclear power generating stations. Communities throughout the country faced with meeting the 1985 goal of zero discharge of pollutants into streams encounter both economic and environmental constraints [Public Law 92-500, 1972]. The high costs of providing primary, secondary, and especially tertiary treatment by conventional methods place an economic burden on communities, especially on the smaller ones typically found in rural areas.

Several wastewater management alternatives exist, including (1) advanced biological treatment, (2) physical-chemical treatment, and (3) land treatment. Communities upgrading their treatment systems must determine which individual or combination of these treatment methods has the greatest potential for meeting both economic and environmental constraints.

The concept of land treatment is receiving increased attention as an alternative wastewater management approach [Dalton and Murphy, 1973; Egeland, 1973; Parizek et al., 1967; Sopper and Kardos, 1973; Thomas, 1973; Williams et al., 1969]. Briefly stated, land treatment involves the use of agricultural land and crops or forest products to absorb and filter nitrates, phosphates, and other elements from wastewater that has undergone primary and, usually, secondary treatment. Water filtered by the soil is then returned to the underground water supply.

The many issues surrounding the use of land for treatment of municipal wastewater, and subsequent land reclamation through soil infiltration and plant growth, encourages a multidisciplinary planning approach. Systematic investigation of institutional, economic, and social issues should be made concurrently with technical and engineering studies. To date, most attention has focused on technical and engineering questions. An objective of this study is to articulate some of these issues and to suggest a framework which social scientists, and agricultural economists in particular, might use as a starting point for further inquiry into the socioeconomic aspects of land treatment.

In the planning and design of a wastewater treatment facility for a city, town, or an area where the requirements for treatment are expected to increase with time, the initial size of the treatment plant and the timing of capacity additions and/or replacements over some time horizon need to be answered in the context of an optimal staging policy. Such a policy is affected by the wastewater treatment requirements, the rates of interest and inflation, construction cost, operating costs, maintenance and repair, service life, and the staging efficiency of the system to be designed.

Recently, the concept of regionalization of wastewater treatment has been suggested as an effective means of meeting the water quality goals at a minimum cost. Although economy of scale provides the primary incentive for regionalization, a host of other advantages such as more qualified operating personnel and higher degrees of automation may be gained through the utilization of this concept.

The recent literature of city planning and regional science contains few analytical studies concerned with facility planning for public urban systems. However, the management of these systems needs a coherent framework for planning which deals with facility size, location, and timing.

This study develops a decision model to use as a guide in planning facilities for a specific wastewater treatment system. An optimization technique will be utilized in selecting the optimum program. The final plan will include the number of treatment plants needed, treatment plant capacities, waste sources to be served by each plant, disposal methods, and plant locations.

Method of Study

The selection of an optimal regional plan over time is a complex problem, the solution of which requires a considerable variety and a quantity of information, a great expenditure of time, money, and a wide diversity of expertise. The optimum plan provides the least cost system of collection, treatment, and disposal of wastewater subject to the physical, financial, and sociopolitical constraints of the region. Choosing an optimal plan from among a large number of alternatives (which involve different construction costs, plant location, facilities and capacity, and farming programs) is quite difficult without a formal model that can accomodate a large number of variables that are determined simultaneously in a dynamic framework. The steps to develop such a model and the links between them are shown in Figure 1.1. The steps consist of two sets: (1) the estimation of the form of cost functions and the values of uncontrolled variables; and (2) the choice of values

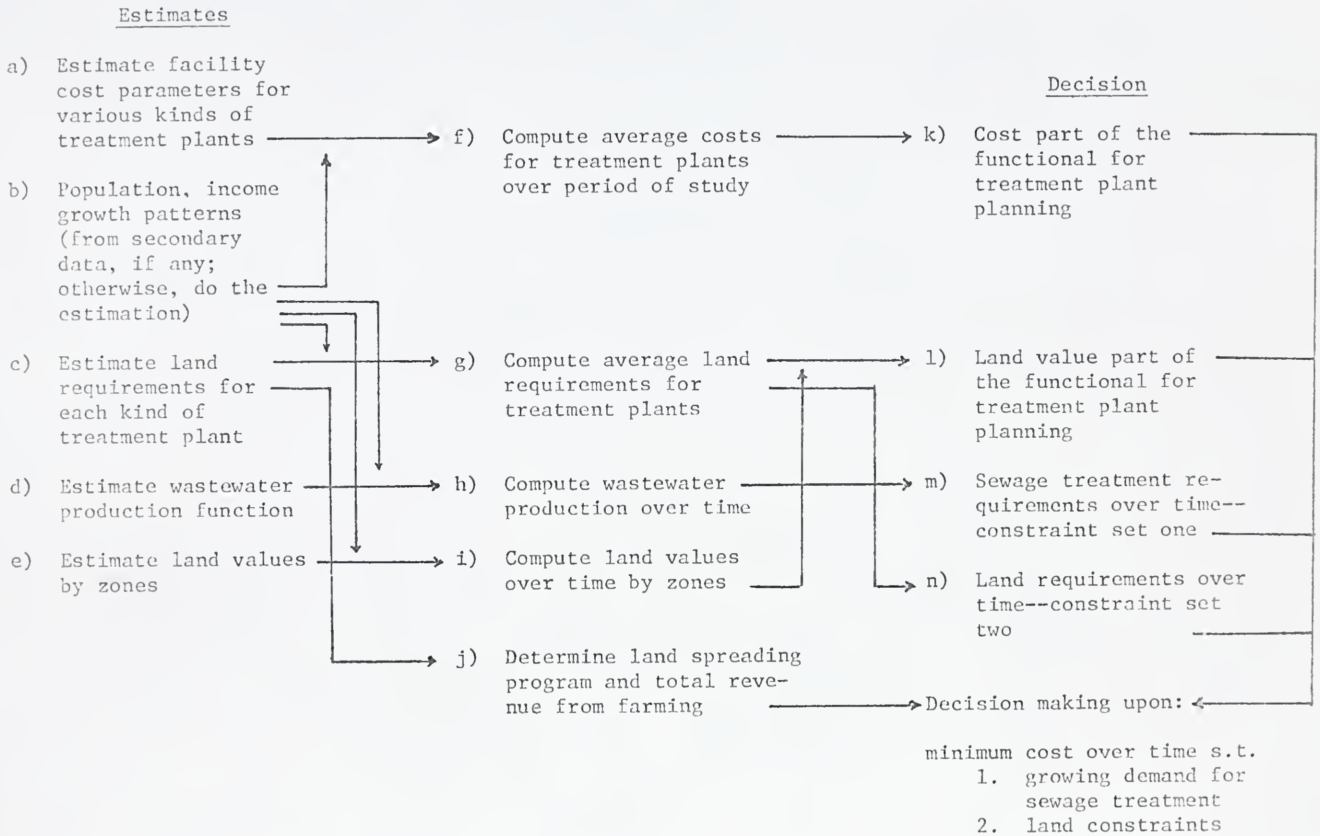

Figure 1.1 Steps in the Development of the Decision Model

of decision variables. Decisions deal with sizes, types, locations, and timing of plants and facilities to be constructed.

In this study, a mathematical optimization model is proposed which will minimize the present value of total expenses over the planning horizon subject to the requirements for wastewater treatment and land availability in the region of interest. Treatment plant facility costs as functions of capacity, land requirements, wastewater production and land values as functions of time and population, and information on zoning and population growth estimates were incorporated in the model to determine a minimum cost expansion program.

Area of Study and Source of Data

Alachua County, Florida was chosen as the study area. The county has a total land area of 568,320 acres or 888 square miles. These figures do not include the large bodies of water representing about 76.4 additional square miles [North Central Florida Regional Planning Council, 1973]. Figure 1.2 shows the location of Alachua County. There are nine incorporated cities or population centers in Alachua County. Only one of these nine incorporated communities has adequate wastewater collection, treatment, and disposal; the remaining eight incorporated municipalities have either privies or septic tanks with the large flow users such as hotels, restaurants, and service stations, primarily located along major thoroughfares, being served by small package plants.

Population estimates for this study were obtained from the estimates provided by North Central Florida Regional Planning Council [1973]. The relationships between capacity and costs, both construction

Figure 1.2   Location of Alachua County

and operation and maintainence, were obtained from EPA studies [Michel and Johnson, 1970; Smith and McMichael, 1969; Smith and Eilers, 1971]. The information about cost increases over time was provided by EPA cost indexes. Other knowledge required to complete this study was obtained from journals, textbooks, and miscellaneous publications on wastewater treatment.

This study developed a procedure to find the optimum number, sizes, and locations of wastewater treatment facilities in Alachua County. The time period involved is from 1975 to 1990, and wastewater sources are only the nine incorporated cities in the county. The concept of regionalization used in this study was that more than one city might transfer its waste to a regional treatment facility in some selected location.

CHAPTER II
RELEVANT ECONOMIC THEORY

This chapter develops a theoretical framework for structuring the mathematical optimization model. Cost minimization theory, location theory, and multidimensional utility analysis are combined to determine the optimum number, size, and location of wastewater treatment plants.

Cost Minimization with Respect to Output

Consider a system of equations consisting of a production function (2.1), a cost equation (2.2), and an expansion path function (2.3):[1]

$$q = f(x_1, x_2) \tag{2.1}$$

$$c = r_1 x_1 + r_2 x_2 + b \tag{2.2}$$

$$o = g(x_1, x_2) \tag{2.3}$$

where q is output, x_1, x_2 are variable inputs, r_1 and r_2 are the respective prices of x_1 and x_2, and b is the cost of the fixed inputs. This system of three equations in four variables can be reduced to a single equation in which cost is stated as an explicit function of the level of output plus the cost of the fixed inputs:

$$c = \phi(q) + b \tag{2.4}$$

The fixed cost must be paid regardless of how much the firm produces, or whether it produces at all. The cost function gives the minimum

[1]This system of equations can be expanded to include more than two variable inputs. [See Ferguson, 1971, pp. 154-168]

cost of producing each output and is derived on the assumption that the entrepreneur acts rationally.

Let the levels of the entrepreneur's fixed inputs be represented by a parameter k, which gives the "size of his plant"--the greater the value of k, the greater the size of his plant. The entrepreneur's short-run problems concern the optimal utilization of a plant of given size. In the long-run he is free to vary k to select a plant of optimum size. The shapes of the entrepreneur's production and cost functions are given in the short-run and depend upon fixed plant size. In the long-run he can choose a production function. Once he has selected this function, i.e., selected a value for k, he is faced with the conventional short-run optimization problems.

Assume that k is continuously variable and introduce it explicitly into the production function, cost equation, and expansion path function:

$$q = f(x_1, x_2, k) \tag{2.1a}$$

$$c = r_1 x_1 + r_2 x_2 + \psi(k) \tag{2.2a}$$

$$o = g(x_1, x_2, k) \tag{2.3a}$$

Fixed cost is an increasing function of plant size: $\frac{d\psi(k)}{dk} > 0$. As before, total cost may be expressed as a function of output level and plant size:

$$c = \phi(q, k) + \psi(k) \tag{2.4a}$$

The entrepreneur's long-run total cost function gives the minimum cost of producing each level of output as a function of plant size. This function is the envelope of the short-run functions: it touches each and intersects none. Write the equation for the family of short-run cost functions (2.4a) in implicit form:

$$C - \phi(q, k) - \psi(k) = G(C, q, k) = 0 \qquad (2.4b)$$

and set the partial derivative of (2.4b) with respect to k equal to zero:

$$G_k(C, q, k) = 0 \qquad (2.4c)$$

The equation of the envelope curve (the long-run cost curve) is obtained by eliminating k from (2.4b) and (2.4c) by solving for C as a function of q, i.e.:

$$C = \phi(q) \qquad (2.4d)$$

Long-run total cost is a function of output level, given the condition that each output level is produced in a plant of optimum size.

Since average cost equals total cost divided by output level, the minimum average cost of producing a particular output level is attained at the same plant size as the minimum total cost of producing that output level. The long-run average cost curve can be derived by dividing long-run total cost by output level, or by constructing the envelope of the short-run average cost curves. The two constructions are equivalent.

Generally, long-run average cost (LAC) is considered as a planning device, which given the state of the arts would tell an entrepreneur the plant size which will enable him to produce a desired output level at the least possible cost per unit. The significance of plant size in relation to the plant costs results from the nature of the economies of scale.

The possible existence of substantial scale economies which would permit relatively large treatment plants to process their wastewater at lower average cost per unit than relatively smaller treatment plants is a key factor in stimulating interest in regional wastewater treatment. The principal basis of scale economies is specialization, or the division of labor--a phenomenon Adam Smith deemed so central that he devoted the first three chapters of Wealth of Nations to it. In Smith's view, great increases in the productivity of labor (and hence great reduction in product cost) were due to three repercussions of the division of labor: an increase in worker dexterity, the saving of time commonly lost in "passing from one species of work to another," and "the invention of a great number of machines which facilitate and abridge labor, and enable one man to do the work of many."

A somewhat different basis of scale economies is found in the process industries such as petroleum refining, chemical production, cement making, glass manufacturing, and steam generation. The output of a processing unit tends within certain physical limits to be roughly proportional to the volume of the unit, other things being equal; while the amount of materials and fabrication effort (and hence investment cost) required to construct the unit is more apt to be proportional to the surface area of the units reaction chambers, storage tanks, connecting pipes, etc. Since the area of a sphere or cylinder of constant proportions varies as the two-thirds power of volume, the cost of constructing process industry plants can be expected to rise as the two-thirds power of their output capacity, at least up to the point where they become so large that extra structural reinforcement and special fabrication techniques are required. There is considerable empirical support for the existence of this "two-thirds rule," which is used by engineers in estimating the cost of new process equipment [Haldi and Whitecomb, 1967; Moore, 1959; Schuman and Alpert, 1960].

Still another benefit of size arises from what E. A. G. Robinson calls "the economies of massed reserves" [Robinson, 1958, pp. 26-27].

A firm anxious to maintain continuity of production must hold equipment in reserve against machine breakdowns. A firm large enough to use only one specialized machine may be forced to double its capacity if it insists on hedging against breakdown; the larger firm with numerous machines can obtain virtually the same degree of protection by holding only a small proportion of its capacity in reserve. Likewise, the number of repairmen a company must employ to provide any stipulated amount of service in the event of random machine failure rises less than proportionately with the number of machines in operation [Whitin and Peston, 1954].

Two other common arguments are the theory of "perfect divisibility" promoted by Kaldor [1943] and Lerner [1946, pp. 186-199], and the theory of "proportionality" developed by Chamberlin [1948]. The theory of perfect divisibility states that the imperfect divisibility of factors explains economies of scale and that with perfect divisibility the economies of scale would be absent. In criticizing the theory of perfect divisibility, Chamberlin argued that it neglects the effects of divisibility of the efficiency of factors. Rather, he claimed that all economies of scale will be explained by the proportion of factors. The theory of proportionality indicates that there is a certin optimum proportion of factors, and because factors are obtainable only in discrete units, this optimum proportion can be closely approximated only when the aggregate of factors is large. In other words, small scale production will be relatively inefficient in achieving these optimum proportions.

It is quite clear that economies of scale do exist, and that unit costs decline with increases in plant and firm size, at least within limits. However, there are several reasons for believing that scale economies are limited. First, in nearly all production and distribution operations the realization of scale economies appears to be subject to diminishing returns. Sooner or later a point is reached at which all opportunities for making further cost reductions through increased size are exhausted. Second, it is possible that rising unit costs related to the difficulty of managing an enterprise of increasingly large scale will offset and eventually overwhelm the savings attributable to high-volume production and distributions [Robinson, 1958, Chapters 3, 10, 12; Coase, 1937; Williamson, 1967]. A third major influence which may prevent economies of scale from being realized indefinitely is the cost of transportation.

The theory of the firm implies that, under pure competition, individual firms tend to operate at equilibrium in the long run, seeking to minimize the long-run cost with respect to output [Leftwich, 1966, pp. 167-177]. The number and size of plants of a given firm are assumed to be determined within the equilibrium conditions. However, wastewater treatment in Alachua County is a regulated utility subject to the control of a single authority. It is a local monopoly and its size is determined largely by the extend of local demand. The distinction between perfect competition industries on the one hand and regulated and imperfectly competitive industries on the other is that, in the former, the size of the market plays no part in determining the size of firm but merely determines the number that can survive, while in the public utility type of industry the spatial distribution of demand determines both the number and relative scale of the firms in the optimal (cost-minimizing) setup.

The Theory of Location

The basic concept of location theory is to incorporate assembly costs into production costs as the basis for determining the cost minimizing conditions. This combination overcomes the shortcomings of neglecting the selection of location as a production activity in the pure theory of the firm. Since the production origins and plants are generally not at the same location, the assembly costs are incurred while transferring the raw material from production origins to plants. Furthermore, the marketing costs incurred while transporting final products from plant site to market should also be included in the analysis. Assembly costs consist of two parts in this study. The collection costs, which relate to the process of removing the sewage from the site of production by small sewer; and the transmission costs, which relate to transporting the sewage from the small sewers by larger sewers to the treatment site. Those costs are directly related to the distance from the site of production to treatment site, the amount of flow transmitted, and the difference in elevation between the two sites to be joined by sewers.

The pure theory of the firm must be combined with the theory of location in order to interpret the joint problem with which this study is concerned. The incorporation of assembly activities into the production process makes the goal of the firm one of minimizing the total combined cost of assembly and production rather than those associated with production alone.

While assembly is clearly external to the operations of a particular plant, both plant operations and transportation are integral parts of the joint function. In order to minimize the production cost, the firm seeks to gain the economies of scale by increasing plant size. However, as the scale of plant increases, there will be accompanying changes in the magnitude of the required assembly costs of raw materials as well as the required costs of disposing of its final products.[2] More specifically, increases in plant size will be associated with expanded supply requirements, and hence, with increased assembly costs and disposal costs. Therefore, potential economies of scale will gradually be offset by increases in these costs.

For instance, consider two communities, A and B, which both have a need for wastewater treatment by means of conventional activated sludge and associated processes. If neither community has an existing wastewater treatment plant and each community needs a one mgd (million gallon per day) plant, the two alternatives are for each community to build and operate its own plant or for some joint effort with one plant. Assume the costs for a single one mgd plant is 25.5 cents/kgal, 22 cents/kgal for a two mgd plant and pipeline cost of 1.71 cents/kgal/mile. Under these assumptions, if two communities are more than 4.1 miles apart, each community would build a one mgd plant.[3] The same kind of argument can be expanded to include more than two communities with different wastewater treatment requirements.

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[2] Disposal costs for an effluent plant are somewhat analogous to marketing costs for a firm producing consumer goods.

[3] The breakeven length pipeline (L) is calculated by equating the total daily cost of the two alternatives and solving for the length of the pipeline at the breakeven point, i.e., to solve (25.5) x 1000 + 25.5 x 1000 = 1.71 L x 1000 + 22.0 x 2000 for L, which gives L = 4.1 miles.

However, the potential location for a plant need not be situated in a site of demand or supply. The question is how location decisions are made. In the ideal case they are made with perfect knowledge of costs and benefits at alternative locations, and they are made so as to maximize net benefits from operations at the optimal location. Often in the real world case, perfect knowledge is replaced by error and an adverse reaction to risk, and the search for optimal locations is reduced to a search for a satisfactory location.

Transport systems were built to promote interactions over space, and prevailing location theory models are largely transportation oriented. To study the effect of cost of geographic space on the location of human activity let us examine the location problem in general terms rather than in terms of specific industry case studies. We shall consider only manufacturing activity and will assume that wage, interest, and other prices are equal everywhere. Only transportation charges which vary with distance are considered in the analytical approaches presented below.

Problems on location analysis can be classified into two major structural categories.

A. Location on a plane, which is characterized by

1. an infinite solution space. That is, central facilities may be located anywhere on the plane and are confined neither to nodes of the network nor to points on the links between these nodes.

2. distance measurement according to a particular metric. One example is the Euclidean metric where

$$d_{ij} = ((x_i - x_j)^2 + (y_i - y_j)^2)^{\frac{1}{2}}$$

d_{ij} = the distance between points i and j,

x_i, y_i = the coordinates in a rectangular system of the i^{th} point.

Another example is the metropolitan metric where

$$d_{ij} = |x_i - x_j| + |y_i - y_j|.$$

B. Location on a network which is characterized by

1. a solution space consisting of the points on the network (both nodes and points on the arcs which join the nodes),

2. distance measurement or time measurement along the network,

d_{ij} = the length (time) of the shortest path [Cooper, 1967] from node i to node j.

Alfred Weber [1909] pioneered the Location Theory. He considered the location of an industry between two resources and a single market where the criterion was minimization of transportation cost. However, it is only two decades since the advent of mathematical programming and computer-aided computation that the problem has received real attention from the standpoint of research.

Werson et al. [1962] presented one of the earliest modern considerations of location problems. They located solid waste disposal sites to minimize hauling costs in a metropolitan environment. Travel was assumed to be along the rectangular grid which typifies many American cities. An optimal single disposal site was determined by linear programming to be at the median of the generating sites.

Beginning with the formulation of Cooper [1963] and Kuhn and Kuenne [1962], interest in location analysis has quickened. Their work which appeared independently described an iterative process for solving the generalized Weber problem. The problem is to find the single point which minimizes the sum of the weighted Euclidean distances to that point. The objective is

$$\text{minimize } z = \sum_{i=1}^{n} w_i d_i$$

where:

w_i = the weight attached to the i^{th} point (goods demanded, resources sent, population, etc.);

d_i = $((x_i - x)^2 + (y_i - y)^2)^{\frac{1}{2}}$, which is the Euclidean distance from point i to central point;

x_i, y_i = the location of the i^{th} point relative to some fixed cartesian coordinate system;

x, y = the unknown coordinates of the central point;

n = the number of points served.

Partial differentiation with respect to x and y yields a pair of equations that are the first order conditions for a minimum:

$$\frac{\partial z}{\partial x} = \Sigma_i \frac{w_i (x_i - x)}{d_i} = 0 \qquad (2.5)$$

$$\frac{\partial z}{\partial y} = \Sigma_i \frac{w_i (y_i - y)}{d_i} = 0 \qquad (2.6)$$

Somewhat more attention has been devoted to problems of locating central points on a network. The problem of warehouse or plant location has the following general characteristics. Given a number of demand areas of a certain product, each with a demand D_i, and a number of alternative sites where facilities may be built to satisfy these demands, determine where the facilities should be placed and which demand areas are to be served by a given facility. The objective is that the sum of the transportation cost and the amortized facility cost is minimized.

A tradeoff exists between facility and transport costs; clearly, the greater the number of well-placed facilities, the lower will be the cost of distribution. But as shipment cost decreases, the investment in facilities must rise. At some number of facilities the total cost should be a minimum. Beyond that point, the cost of adding a facility exceeds the savings in distribution cost. It is assumed that both the number of demand areas for products and the number of plant or warehouse sites are finite.

Maranzana [1964] considered warehouse location where distances are not Euclidean but are measured on the road network. He also utilized an heuristic procedure to locate a specified number of warehouses to serve a region of known demands. His criterion was the minimization of transport costs. Kuehn and Hamburger [1963] also presented a heuristic method for warehouse location; their approach was to minimize the sum of transport and warehousing costs.

ReVelle and Swain [1970] consider a location problem; their objective was the minimization of average time or distance which people must travel to the facilities. The problem is constrained by a fixed number of facilities. The model was structured as a 0-1 mix integer programming problem with facilities restricted to nodes of the network.

In this study, equations (2.5) and (2.6) were used to find the potential sites for treatment plants. Euclidean metric distance measurement was used to determine the optimal locations for wastewater treatment facilities. The solution space consists of potential sites and sources of wastewater treatment demands.

Multidimentional Utility Analysis

Since their inception, cost minimizing models for firm behavior have certainly not been without their critics. But for the most part the critics have failed to propose substantive alternatives for theoretical use. An approach not directly involving simply cost minimization was suggested by Scitovsky [1943]. In particular, he showed that if an entrepreneur attempts to maximize satisfaction, he will expend the same amount of effort as if he were attempting to maximize profit only in the special case in which the marginal rate of substitution between entrepreneruial activity and money income is independent of the level of money income. The point of interest is the applicability of multidimensional utility theory to a certain class of microeconomic problems.

The theory of multidimensional vector ordering, or what is now more generally called lexicographic ordering, has the following meaning. Consider two alternatives, which may be bundles of commodities, combinations of lottery tickets, business objectives, etc., i.e., $x^0 = (x_1^0, x_2^0, \ldots, x_n^0)$ and $x^1 = (x_1^1, x_2^1, \ldots, x_n^1)$. Let u be a preference index function. A regular ordering ranks $u(x^0) > u(x^1)$ if, and only if, $x_i^0 \geq x_i^1$ for all i and the strict inequality holds for at least one component.

In a lexicographic ordering a hierachy of wants is recognized; the components of the vector x are not regarded as equally important. For convenience, let the elements of each vector be numbered so that x_1 is more important than x_2, x_2 is more important than x_3, etc. Then $u(x^0) > u(x^1)$ if $x_1^0 > x_1^1$, irrespective of the relationships between x_i^0 and x_i^1, for i = 2, 3, ..., n. If $x_1^0 = x_1^1$, comparison is based upon the second component. Thus, $u(x^0) > u(x^1)$ if $x_1^0 = x_1^1$ and $x_2^0 > x_2^1$, etc. Proceeding in this manner, vector elements associated with variables lower in the hierachy of wants are considered only after the higher order wants are satisfied [Encarnacion, 1964].

Let us consider a wastewater treatment system in a basin, in which it is assumed that the policy makers attempt to minimize wastewater treatment cost for the entire basin subject to maintaining a satisfactory level of water quality. This model actually has two possible outcomes. First, if the level of water quality is less than the satisfactory level, the policy makers disregard the cost minimization goal and behave as though they were purely radical environmentalists. Second, if the satisfactory level of water quality is achieved, the policy makers would seek to minimize wastewater treatment costs for the entire basin. In the terminology of multidimensional utility analysis, level of water quality is the dominant component and cost minimizing is the subordinate one.

Denote the level of water quality by x_1 and costs by x_2. Thus any situation is represented by the vector $x = (x_1, x_2)$. Suppose the satisfactory level of water quality is x_1^*. According to the description of the model, further water quality does not enhance the utility or satisfaction of the policy makers. In other words, if $u(x)$ is the utility function,

$$\frac{\partial u}{\partial x_1}\Big]_{x_1 > x_1^*} = 0$$

Thus the optimum vector x^* is found by selecting the policy that minimizes x_2 (costs) subject to $x_1 \geq x_1^*$. In particular, let us compare two situations $x^0 = (x_1^0, x_2^0)$ and $x^1 = (x_1^1, x_2^1)$. The former is preferred to the latter if, and only if, $x_1^i \geq x_1^*$ for $i = 0, 1$, and $x_2^0 < x_2^1$. If this problem is not feasible, i.e., $x_1^i < x_1^*$ for $i = 0, 1$, the optimum vector x^* is the one whose first component is greater ($x_1^i > x_1^j$ for $i \neq j$).

This simple two-variable model can easily be generalized. Suppose there are M goals $x_1, x_2, \ldots, x_m$ arranged in order of descending importance. Further, let each goal be defined so that

$$\frac{\partial u}{\partial x_i}\Big]_{x_i < x_i^*} > 0 \text{ and } \frac{\partial u}{\partial x_i}\Big]_{x_i \geq x_i^*} = 0$$

Every possible situation is described by a vector $x = (x_1, x_2, \ldots, x_n)$; and the optimal vector x^* is found by selecting the set of policies which solves the following constrained maximization (or minimization) problem: maximize x_m subject to $x_i \geq x_i^*$ for $i = 1, 2, \ldots, m-1$. If this problem is unfeasible, the least important goal (x_m) is dropped from consideration. The new problem accordingly becomes: maximize x_{m-1} subject to $x_i \geq x_i^*$ for $i = 1, 2, \ldots, m-2$. One thus works in sequence until a feasible problem is determined, all lower ordered goals being discarded in route. If goal $k(<m)$ is the least important objective for which a feasible problem exists, the vector x^0 is the optimal vector if, and only if, $x_i \geq x_i^*$ for $i = 1, 2, \ldots, k-1$ and $x_k^0 > x_k^j$ for all $j \neq 0$.

In this study, treating wastewater is the dominant component and cost minimizing is the subordinate one. Possible wastewater treatment methods will be investigated, and their costs will be estimated; a decision will be made according to the framework of multidimensional utility analysis.

CHAPTER III
A GENERAL MODEL FOR REGIONAL WASTEWATER TREATMENT

Regionalization may consist of the centralization of administration (separate sewerage systems operated by a single authority) or one central plant serving several municipalities. There are two ways to centralize the wastewater treatment for the second case. One suggestion which has been made to control pollution along reaches of a system is to collect the sewage from all the cities and firms along the stream and treat it at one central downstream location. Another suggestion often made is that small outlying cities or villages transport their waste to a regional treatment facility in a large city. The feasibility of such proposals can be judged by comparing the cost of transporting waste with the treatment savings which can be realized.

In order to meet the condition that the available treatment plant capacity at any time during the study period is sufficient to meet the requirement, there are many expansion policies that can be chosen. Planning an expansion scheme involves the choices of choosing plant capacity, building site, and treatment facilities (such as land spreading versus integrated biological-chemical systems and the like). Also, different rates of interest and inflation can change the preferred ordering of alternative schemes.

In this chapter, a mathematical model is developed for the purpose of choosing an expansion scheme which minimizes the present value of investment given construction costs and wastewater treatment requirements over time.

The Model

The primary factors which will be considered in selecting a regional plan in this study include:

a) waste sources to be served;

b) number and capacities of treatment plants needed;

c) treatment plant locations;

d) desired degrees of treatment;

e) collection system; and

f) cost functions.

Arrangement of outfall structure, cost allocation among participants, methods of financing, and methods of implementation will not be considered in the model. The influence of factors (a) - (f) on the selection of an optimal regional wastewater management system is described more fully below.

The development of a sound regional wastewater treatment plan requires a full knowledge of the major existing and potential sources of wastes. The type of the treatment facility, physical, chemical, or biological, as well as the design of the collection system, pumping stations, and treatment depends on the quantity and characteristics of the wastes. Therefore, characterization and quantification of all the major sources, both municipal and industrial, within the region may be considered as one of the most important factors in the development of an effective wastewater management plan.

The locations of wastewater treatment plants constitute a major factor in the overall plan for optimization of wastewater management in a region. Such factors as the water quality criteria, the distributions of waste sources, cost of treatment facility, cost of pumping stations, and interceptor sewers must be considered.

A general model is to supply answers regarding the location of treatment facility, capacities, and the number of treatment plants. Assume that we have I wastewater sources, J potential regional and/or individual plant locations, K types of treatment plant, and a planning horizon from time 1 to T. In the following relations:

i	refers to waste source;	$i = 1, \ldots, I$
j	to plant location;	$j = 1, \ldots, J$
k	to type of treatment plant;	$k = 1, \ldots, K$
t	to time period;	$t = 1, \ldots, T$

d_{it} to amount of wastewater generated at source i at time t;

CC_{jkt} to present value of wastewater treatment costs at location j for type k facility at time t;

CS_{ijt} to present value of wastewater transmission cost from source i to location j at time t;

RC_{jkt} to required wastewater treatment capacity at location j for type k facility at time t;

RS_{ijt} to required wastewater transmission capacity from source i to location j at time t;

C_{jkt} to existing wastewater treatment capacity at location j for type k facility at time t;

S_{ijt} to existing wastewater transmission capacity from source i to location j at time t;

CX_{jkt} to new wastewater treatment capacity to be built at location j of type k at time t;

SX_{ijt} to new wastewater transmission capacity to be built from source i to location j at time t; and

Z_{ijt} to the amount of waste flow from i to j at time t.

Specifically the model can be stated as follows:

$$\text{Minimize} \sum_{j,k,t} (CC_{jkt} + CS_{ijt}) \tag{3.1}$$

Subject to the constraints:

$$\sum_{j=1}^{J} Z_{ijt} \leq d_{it} \qquad \text{for all i and t} \tag{3.2}$$

(waste at each source must be satisfied)

$$\sum_{i=1}^{I} Z_{ijt} \leq \sum_{k=1}^{K} RC_{jkt} \qquad \text{for all j and t} \tag{3.3}$$

(the amount of waste flow into location j must be less than or equal to treatment capacity at location j)

$$Z_{ijt} \leq RS_{ijt} \qquad \text{for all i, j, and t} \tag{3.4}$$

(the amount of waste flow from source i to location j at time t must be less than or equal to its required transmission capacity)

$$RS_{ijt} - S_{ijt} \leq SX_{ijt} \qquad \text{for all i, j, and t} \tag{3.5}$$

(the difference between required capacity and existing capacity for transmission must be less than or equal to the new capacity to be added for the waste flow from source i to location j at time t)

$$RC_{jkt} - C_{jkt} \leq CX_{jkt} \qquad \text{for all j, k, and t} \tag{3.6}$$

(the difference between required capacity and existing capacity for treatment must be less than or equal to the new capacity to be added for type k facility at location j at time t)

where CC_{jkt} and CS_{ijt} are functions of CX_{jkt} and SX_{ijt}, respectively.

This model involves three dimensions. These are time, space, and types of facility. In order to solve this model one needs information about the amount of waste generated at each source, the cost functions of treating and transporting the waste, and the locations for regional wastewater treatment plants. In the following sections we will discuss briefly how this information was obtained for this study. A brief discussion will be given on the basic ideas which have been built into this general model; then a way of solving this model will be introduced as a preview for the next three chapters.

Wastewater Production

Wastewater comes from four primary sources: municipal sewage, industrial wastewater, agricultural runoff, and storm water and urban runoff. Estimation of municipal and industrial wastewater flows and loadings can be done in one of several ways, based on knowledge of past and future growth plans for the community, sociological patterns, and land-use planning.

Municipal and industrial (M&I) water use rates are affected by variables that may be grouped into two broad categories [Department of Water Resources, California, 1968]:

1. Climatic factors such as temperature, rainfall, wind speed, and so on.
2. Man-made factors which further divided into two groups:
   a) Residential-related factors such as economic level, education, price of water, family size and age, metering and sewering.
   b) Other urban related factors such as greenery, kind of community, changing industrial water requirements, water production and use measurements, population served, and other factors such as worn flow meters and inadequate distribution systems.

Watking [1968] points out about the same results in a study of sociological perspective of water consumers in South Florida households.

An aggregate wastewater production function can be specified by the following relationship:

$$d_{it} = f(w_{it}, PN_{it}, M_{it}) \tag{3.7}$$

where:

d_{it} is the amount of wastewater at zone i at time t;

w_{it} is the price of water at zone i at time t;

PN_{it} is the population served by the treatment plant at zone i at time t; and

M_{it} is the income level at zone i at time t.

In an urban water demand study, Hanke [1968] pointed out that average household water uses differ little between metered and unmetered areas, but sprinkling uses and peak demand differ considerably. In other words, household water uses are price inelastic and sprinkling uses are price elastic. Since in most cases only household wastewater which is not sensitive to the price of water goes into sewage system, equation (3.7) may be simplified as follows:

$$d_{it} = f^{*}(PN_{it}, M_{it}) \tag{3.8}$$

Cost Functions

The cost of a regional wastewater treatment network is a function of a number of variables. Some of these variables are internal to the technology of the service in question. Others are a function of conditions which are unique to a certain site and life style which the planner usually accepts as given, while a third set involves factors which relate to the urban morphology (form and structure). This last set of factors will be regarded as choice variables from the point of view of the city planner who is involved in studying the cost implications of alternative zoning and development policies but will be considered as given in this study.

Emphasis on regional planning usually centers around optimization of the collection, treatment and disposal of wastewater in the region to meet a set water quality goal at a minimum cost to the region. A host of alternative solutions must be entertained and each alternative has an associated cost function. These cost functions include cost of facilities, construction, operation and maintenance of collection, and final disposal. Although economies of scale provide the main incentive to a regional wastewater treatment system, it is not always true that a single large treatment plant for the entire region will provide the least cost system, nor is it always possible to have a single plant. This is, of course, due to the fact that the location and the capacity of the treatment facility can not be independent of other factors such as waste sources to be served, the topography of the region, length of interceptors, and locations and number of existing sewage facilities. The final analysis in the regional plan must, therefore, consider trade-offs between combining treatment facilities, combining and/or abandoning transmission facilities, and final disposal methods.

In this study, cost functions of the wastewater treatment facilities will be divided into two categories--cost functions of collection systems, cost functions of treatment plant facilities (secondary and advanced). Furthermore, each category of cost functions will be subdivided into two subcategories, i.e., construction cost functions and operation and maintenance cost functions.

Since an optimal staging policy is also affected by the rate of interest and inflation, one dollar spent today will not be considered equivalent to one dollar spent at some future date. The decision problem at hand is a multipoint-input, multipoint-output allocative problem [Henderson and Quandt, 1958, p. 244] with the demand given for output treatment capacity at each point of time.

To project year-by-year operating costs for each segment of the proposed system, a present value of future expenditures scheme was used in the optimization model. A basic operating cost for the present year was set for each treatment plant and transmission line. The value was then inflated at a parameterized rate to reflect increased labor and maintenance expenditures in the future. The present value of the resulting series of expenditures was then added to the initial cost of each system component to obtain a present value of costs over the planning horizon.

Let i_t be the market rate of interest and γ_t be the inflation rate connecting marketing date t-1 and t. Then the present value of one dollar payable at the end of t^{th} marketing period is

$$\left[\prod_{\tau=1}^{t} (1 + \gamma_\tau)\ (1 + i_\tau)^{-1} \right] = V_t \quad t = 1, \ldots, T \tag{3.9}$$

For example, the total present value of costs for a type k treatment facility at location j at the end of time t is

$$CC_{jkt} = (FC_{jkt} + FM_{jkt})\ V_t \tag{3.10}$$

where FC_{jkt} and FM_{jkt} are the construction cost and operation and maintenance costs for type k facility at location j at time t, respectively. This same rule will be used to calculate the present value of a transmission system.

In order to solve this general model, we need information about the potential sites for individual and/or regional treatment plants. Theoretically, a regional treatment plant can serve from two to nine cities; therefore, for a nine-city problem, such as this study, we end up with $\sum_{i=1}^{9} \binom{9}{i}$ potential sites, where $\binom{9}{i}$ represents the number of combinations of choosing i cities out of nine cities. This study will be started from the estimation of wastewater production, finding potential sites for regional treatment plants, collection cost data, and eventually reaching a solution for this general model.

The first dimension to be considered in this study is the consolidation of treatment plants over space. This dimension is included because the existence of scale economies may permit relatively large treatment plants to process their wastewater at lower average cost per unit. Thus, the cost for treating wastes from several sources at a regional plant may be lower than the total cost if wastes were treated at each source. There is a tradeoff between the gains from scale economies and the losses incurred by constructing transmission pipelines.

The second dimension to be considered in this study is the consolidation of treatment plants over time. Since the demands for wastewater treatment increase with time and the inflation rate exceeds the interest rate there may be a net gain by building a treatment plant larger than necessary. This is the tradeoff between the gains in economies of scale, savings in inflation, and the losses in interests and in operating and maintaining excess capacity,

The third dimension to be considered is the effect of different types of treatment facilities. In this study, we consider only two types of secondary treatment plant, three tertiary processes, and the possibility of substituting tertiary treatment by land treatment.

The problem of consolidation of treatment plants over space was first solved for this problem; the central location model mentioned in Chapter II was used. Then the consolidation of treatment plants over time was incorporated with the consolidation over space, and solved simultaneously. Finally, a feasibility analysis of substituting land treatment for tertiary treatment is presented.

CHAPTER IV
WASTEWATER TREATMENT SITES

In order to develop a working model, the following information is required:

1. potential wastewater sources and potential sites for wastewater treatment plant,
2. the amount of wastewater produced at each source, and,
3. cost functions of wastewater treatment facilities as well as cost functions of transmission pipeline from each wastewater source to the potential sites for wastewater treatment facilities.

This chapter will provide the above information and then compare the potential treatment sites found in this study with those provided by North Central Florida Regional Planning Council [1973, pp. 11.1-11.27].

General Description of the Area

Alachua County is located in the North Central section of the Florida peninsula. The Santa Fe River, on the north, separates Alachua County from Columbia, Bradford, and Union Counties. Putnam County lies along most of the Eastern boundary, with Clay County at the north end. Marion County is at the south end of the east boundary and runs along roughly two-thirds of the south boundary. Levy County borders Alachua County to the south and west, and Gilchrist to the west. All of Alachua County's territory falls within the 29° 25' and 29° 57' parallels of latitude north and the 82° 03' and 82° 40' meridans of longitude west.

The county has a total land area of 568,320 acres or 888 square miles. These figures do not include the large bodies of water representing about 76.4 additional square miles [North Central Florida Regional Planning Council, 1973]. Alachua County lies within the central highlands of the state. The area generally ranges from level or nearly level to gently sloping. Most ground elevations range between 50 and 210 feet above sea level. Climate in Alachua County is mild, with a mean annual temperature of 70.2 degrees and an average yearly rainfall of approximately 52 inches. Precipitation varies from year to year, particularly in the summer months. Alternating wet and dry cycles of several years' duration are observed. Most of the rain, an average of about 36 inches per year, is tropical in nature, falling during the summer months as thundershowers. About 16 inches of the yearly average come as winter rain of the cyclonic or frontal type, usually slow and drizzly and followed by a drop in temperature.

As a result of the increase in population and its changing characteristics, the way in which land is used in the county has two basic land use patterns. Agricultural land use has retained its dominance and is still the primary land use category as it was in the early 1900's. The Gainesville Urban Area has developed as a major urban center at the approximate geographic center of the county. Land use in the urban center is primarily residential and institutional in nature. Commercial land uses, although occupying a relatively smaller number of acres, have developed to support the agricultural, residential, and institutional uses. Table 4.1 summarizes the estimated major land use categories for Alachua County in 1972. The most significant changes expected are

Table 4.1 Estimated Land Uses in Alachua County

	Nonagriculture			Agriculture			
	Public Land	Developed Land	Water Areas	Cropland	Pasture	Forest	Other
% of Total	4.03	9.91	7.71	11.17	20.81	19.16	27.20

Source: North Central Florida Regional Planning Council [1973].

increase in forest lands and urban area, and a decrease in croplands or cultivated areas.

Alachua, Archer, Hawthorne, High Springs, LaCrosse, Micanopy, Newberry, and Waldo are the eight incorporated centers of population in Alachua County exclusive of Gainesville. Their location is shown on Figure 4.1. Melrose, an unincorporated community is situated on the boundary line between Alachua and Putnam Counties.

There are many unincorporated towns within Alachua County. The most important are Arredondo, Campville, Cross Creek, Earleton, Evinston, Fairbanks, Forest Grove, Grove Park, Hague, Island Grove, Lochloosa, Monteocha, Orange Heights, Rochelle, Santa Fe, and Windsor. Most of the rural dwellings are found within the western half of the county. Table 4.2 provides a brief description of each of the incorporated cities.

The city of Gainesville is the only incorporated community with near adequate wastewater collection, treatment, and disposal. Present treatment facilities in Gainesville consist of a 5-mgd high-rate trickling filter plant and the recently completed 4.5-mgd contact stabilization plant. In addition, the city owns a third treatment plant; this

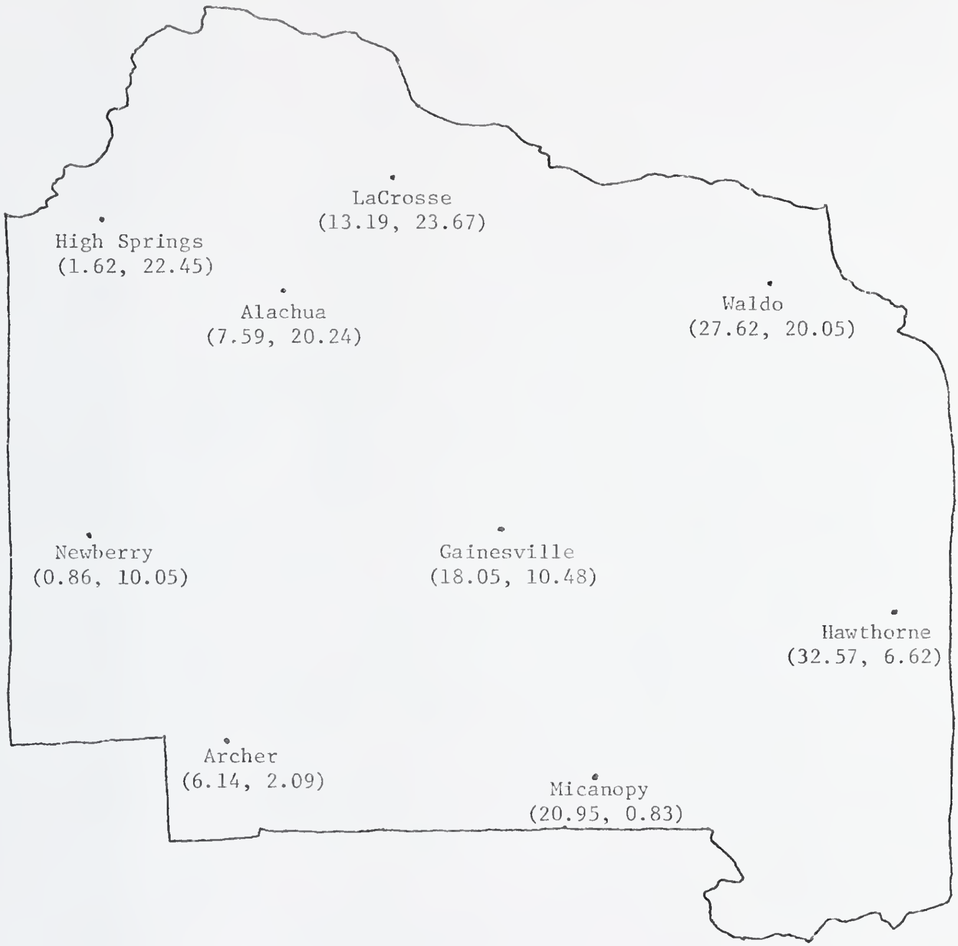

Figure 4.1 Locations of the Incorporated Cities in Alachua County, Florida

Table 4.2 A Brief Description of the Incorporated Cities in Alachua County

Name	Area (sq. miles)	Population		Distance from Gainesville (miles)	Projected Population Levels	
		1960	1970		1980	1990
Alachua	2.0	1,974	2,252	14	3,550	4,450
Archer	1.5	707	898	13	1,110	1,350
Gainesville		29,701	64,510	--	118,849	152,831
Hawthorne	1.0	1,167	1,126	17	1,315	1,480
High Springs	4.21	2,329	2,787	22	3,300	3,945
LaCrosse	1.25	165	365	12	485	600
Micanopy	1.0	658	759	10	860	895
Newberry	1.0	1,105	1,247	13	1,490	1,775
Waldo	1.12	735	800	14	895	995

Source: Black, Crow, and Eidness, Inc. [1967].

is an extended aeration plant with a nominal capacity of 55,000 gallons per day.

The city of Waldo is the only other city providing public sanitary facilities; the present wastewater treatment facility is a 40,000 gallon septic tank, which is grossly inadequate. The remaining eight incorporated municipalities have either privies or septic tanks with the large flow users such as hotels, restaurants, and service stations, primarily located along major thoroughfares, being served by small package plants. Table 4.3 gives an inventory of the treatment plants in Alachua County by their capacities.

Table 4.3 Number and Capacities of the Treatment Plants in Alachua County, December, 1973

	Capacity (million gallons per day)				
	0.01	0.01-0.05	0.05-0.1	0.1-1.0	1.0
Number of Plants	8	14	2	3	3

Source: A computer output provided by Alachua County Pollution Control Board.

As mentioned in Chapter III, the amount of wastewater produced may be estimated as a function of the size of population served, and the income level. However, due to the lack of accurate data on the size of population served,[1] this relationship was not estimated. Instead, an

[1]The monthly sewage treatment operation report submitted by each treatment plant should provide this information. However, a review of those reports submitted by the treatment plants in Alachua County indicated incompletenesses as well as inaccuracies which prohibit meaningful estimation of wastewater production function. Therefore, an average daily flow per capita estimate was used.

average daily flow per capita was used to estimate the wastewater produced at each wastewater source. Assuming a sewage flow of 135[2] gallon per capita per day, Table 4.4 shows the estimates of sewage flow of each city in Alachua County in year 1975, 1980, and 1990, respectively.

Table 4.4 Estimated Wastewater Flows in Alachua County, Florida, by Incorporated Cities for 1975, 1980, and 1990

Name	Wastewater Flows (gal/day)		
	1975	1980	1990
Alachua	456,975 (3,385)	479,250 (3,550)	600,750 (4,450)
Archer	133,650 (990)	149,850 (1,110)	182,250 (1,350)
Gainesville Urban Area	13,729,500 (101,700)	16,044,615 (118,849)	20,632,185 (152,831)
Hawthorne	168,750 (1,250)	177,525 (1,315)	199,800 (1,480)
High Springs	409,050 (3,030)	445,500 (3,300)	532,575 (3,945)
LaCrosse	58,050 (430)	65,475 (485)	81,000 (600)
Micanopy	108,540 (804)	116,100 (860)	120,825 (895)
Newberry	184,275 (1,365)	201,150 (1,490)	239,625 (1,775)
Waldo	114,075 (845)	120,825 (895)	134,325 (995)
Total	15,362,865 (113,799)	17,800,290 (131,854)	22,723,875 (168,325)

Remark: The figures in parentheses are estimated population sizes from North Central Florida Regional Planning Council [1973].

[2] Which is an average daily flow of 73 cities in 27 states in the United States [Loehr, 1968].

After potential wastewater sources and the amount of wastewater produced by each source were determined, the potential sites for wastewater treatment facilities were considered. In order to chose the potential sites, the central location model mentioned in Chapter II was used. The number of potential sites is quite large.[3] As a consequence, the large amount of computer time makes it impractical to find a solution for each potential site using the model presented in the previous chapter. To overcome this problem, a computer program was developed (see Appendix I and next chapter for the details of this program) to scan through all the potential sites, and eliminate those which have higher sum of regional treatment and transmission costs than the sum of individual treatment costs. This computer program used a central location model to determine potential sites and to calculate the transmission costs and the combined treatment costs. The program then compares the sum of transmission and treatment costs with the sum of the treatment costs if each city involved built its own treatment facilities.

Wastewater Transmission Costs

The cost functions for transmission are as follows:

1. The relationship between flow and the diameter of sewers, which minimizes the sum of the cost of frictional power and the debt service for the pipe, estimated in [Smith and Eilers, 1971] as:

$$\text{Economic Diameter (inches)} = 8.55Q^{.463} \qquad (4.1)$$

where:

Q = designed flow in mgd.

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[3]The total number of potential site equals to $\sum_{i=1}^{9} \binom{9}{i} = 491$, where $\binom{9}{i}$ is defined as $\dfrac{9!}{(9-i)!\,(i)!}$.

2. The cost associated with sewers which includes the amortization cost and a small maintenance cost in terms of October, 1970 dollars was estimated [Smith and Eilers, 1971] as follows:

$$\text{Construction costs in dollars per mile} = 1540.7(ID + 2.0436)^{1.37949} \qquad (4.2)$$

where:

ID = inside pipe diameter in inches.

The cost of maintaining the sewer was taken as \$40/yr/mile.

3. The construction cost for pumping stations has been estimated [Smith and Eilers, 1971] as:

$$\text{Construction cost, \$} = 76{,}300Q^{.7682} \qquad (4.3)$$

where:

Q = average flow in mgd.

The operation and maintenance cost for pumping stations has been estimated [Smith and Eilers, 1971] as:

$$\text{cents/1000 gal.} = 1.59Q^{-.263} \qquad (4.4)$$

where electrical power was assumed to cost one cent per kw-hr. The hydraulic efficiency of the pump was taken as 60% and the electrical efficiency of the driving motor was taken as 80%. All costs were keyed to October, 1970.

The Ten State Standards [Great Lakes--Upper Mississippi River Board of State Sanitary Engineers, 1971] require interceptor sewers to be sized to carry 3.5 times the design flow for the plant. This factor was used for sizing both the pipelines and the pumping stations, since the flow of sanitary sewage reaching the treatment plant varies over time, and the capacity of the sewage facility is fixed over the short run.

Excess capacity (capacity above the average daily flow) is necessary to collect and treat the sewage.

The collection and transmission of peak flows may be handled in one of the three ways: (1) sewers could be built to handle the expected peak or some greater flow, (2) a holding tank could be installed to average flows, and (3) some method could be employed which would average the release of flows. Of these three, engineers consider the first as the only feasible alternative. Holding tanks have not been used because there are design problems which engineers feel prevent their use. Averaging at the source of the flows is an alternative which engineers avoid completely.

Wastewater Treatment Costs

Treatment of sewage is the process of removing undesirable materials from the water and/or changing them into less objectionable forms. In the typical plant this is done by a combination of physical and biological processes. In essence, the treatment process uses a more rapid version of the same process which would occur if the wastes were released to the receiving water without treatment.

The selection of a wastewater treatment process or a combination of processes will depend upon: (1) the characteristics of the wastewater, (2) the required effluent quality, (3) the costs and availability of land, and (4) the future upgrading of water quality standards. In this study, two conventional treatment systems will be considered, i.e., high-rate trickling filter system[4] and activated sludge system. Since the high-rate trickling filter systems cannot remove more than about 80% of BOD and SS, most new plants for domestic wastewater treatment are activated sludge plants.

Of course, there are minor variations in the designs of treatment plants. For example, there are different ways to circulate the primary as well as secondary sludge, and there are different designs for returned sludge entering the primary settling tank and the like. However, the cost variations incurred by these different designs are not large, hence these differences in cost will not be considered in this study.

There are several ways one can estimate the construction and operation and maintenance costs of a treatment plant. A cost estimation computer program was developed by Smith [Environmental Protection Agency, 1973b] which allows the consideration of influent waste strength as well as the different combinations of treatment processes. Such a program was purchased from National Technical Information Service and adapted to the IBM 370 system at the University of Florida. However, there were errors in the program which precluded its use.[5]

EPA [1973a] has estimated cost equations with regression analysis using data on accepted bids for construction of new municipal wastewater

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[4]The differences of design between a high-rate trickling filter system and a standard-rate (or low-rate) trickling filter system depend on their hydraulic loading, 200-1000 gpd per sq. ft. for high-rate operation, and 25-100 gpd per sq. ft. for standard-rate operation [Fair et al., 1971].

[5]Treatment plant design examples provided by National Technical Information Service were used to test the computer program, however, the computer output showed that during the calculation some logarithm and exponential functions had illegal arguments. Several attempts have been made without success to correct these errors, hence the program was not used in this study.

treatment plants in several states between 1967 and 1969 as a function of design flow. Costs were updated to September 1972 dollars by using the EPA Sewage Treatment Plant Construction Cost Index. EPA's estimates provide another means of estimating costs. Their estimates were as follows:

1. For high-rate trickling filter system:

$$AC = 852049.58\ M^{-.37461} \tag{4.5}$$

2. For activated sludge system:

$$AC = 699835.09\ M^{-.3544} \tag{4.6}$$

where:

AC = average construction cost, and

M = amount of design flow in mgd.

And estimates of operation and maintenance cost collected from reports on 600 plants between 1968 and 1970 in January 1968 dollars have the following relationships [Michel and Johnson, 1970]:

1. For high-rate trickling filter system:

$$TC = 31959.50\ M^{.6496} \tag{4.7}$$

2. For activated sludge system:

$$TC = 46989.41\ M^{.6023} \tag{4.8}$$

where:

TC = total annual operation and maintenance cost, and

M = amound of design flow in mgd.

A third way of estimating wastewater treatment costs is the application of the six-tenths rule [Berthauex, 1972; Williams, 1947; Chilton, 1950; Eckenfelder and Ford, 1969]. Under this rule, the cost-capacity relationship has the following form:

$$\frac{\text{Cost of Plant A}}{\text{Cost of Plant B}} = \left(\frac{\text{Capacity of Plant A}}{\text{Capacity of Plant B}}\right)^M$$

or

$$C_a = C_b(Q_a/Q_b)^M = KQ_a^M$$

where:

C_a = cost of an item of capacity Q_a,

K = base cost factor and equals C_b/Q_b^M, and

M = measure of the economy of scale.

The name "Six-tenths rule" arose because the exponent M is often about 0.6 for chemical processing plants. The rule not only applies to scaling-up the costs of an entire plant but shows that the exponent varies with the type of plant under construction. Some of the estimates of factor M are shown in Table 4.5.

Table 4.5 Cost-Capacity Factors for Municipal Wastewater Treatment Plants

Type of Plant	Size Factor (M)	
	(1)	(2)
Activated Sludge	0.77	0.65
Trickling Filter	0.60	0.62

Source: (1) from Berthauex [1972]. (2) from EPA [1973a].

In this study, the estimated equations (4.1) through (4.8) by EPA were used. All the cost figures were adjusted to September 1974 dollars. Equations (3.9) and (3.10) were used to calculate the present values of 1975, 1980, and 1990 cost figures in terms of September 1974 dollars.

Tertiary Treatments

Tertiary treatment may be categorically defined as treatment for the removal of pollutants not removed by conventional treatment processes (activated sludge, trickling filters, etc.). These pollutants will include suspended solids (SS), biochemical oxygen demand (BOD), refractory organics (usually reported as chemical oxygen demand (COD) or total organic carbon (TOC)), nutrients (nitrogen and phosphorus), and inorganic salts. In the United States today, increasing emphasis is being placed on the removal of phosphorus and the removal of unoxidized nitrogen which will exhibit a long-term oxygen demand in the receiving waters.

The lime clarification process is used primarily for the removal of phosphorus and suspended organic matter. An additional benefit is the increasing pH resulting from lime addition which makes ammonia nitrogen available for removal by air stripping. Even though many problems associated with the use of ammonia stripping processes remain to be solved, it is presently viewed as the most promising process for removing ammonia nitrogen from wastewater. A process employed in Lake Tahoe is shown in Figure 4.2. The effluent characteristics are shown in lower part of the same figure.

The estimated cost equations for three tertiary treatment processes to be used in this study from the data provided by [Smith and McMichael, 1969] are presented below:

1. Two clarifier lime clarification process without chemicals:[6]

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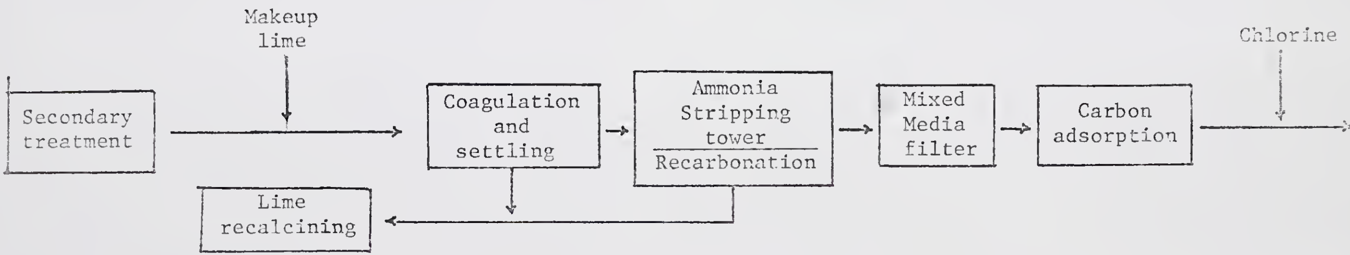
[6]There is some evidence that a coagulant aid such as iron might be required in the second clarifier. Since the need for this chemical is not clearly established, it was not included in the cost.



Effluent Concentration mg/l				
BOD	20-40	1-3	< 1	< 1
COD	80-160	40-70	30-60	1-15
SS	> 20	1-5	< 1	< 1
PO_4	25-30	1-2	0.1-1.0	0.1-1.0
N	29-38	15-35	< 2	< 2

Figure 4.2 Tertiary Treatment Processes, Lake Tahoe [Slechta and Culp, 1967]

Construction cost (million dollars) =

$0.128371Q^{.776102}$ (4.9)

O&M cost (dollars/day) = $62.8518Q^{.692928}$ (4.10)

2. Lime recalcination plus make up lime for use with lime clarification:

Construction cost (million dollars) =

$0.196977Q^{.508007}$ (4.11)

O&M cost (dollars/day) = $49.3768Q^{.728564}$ (4.12)

3. Ammonia stripping of lime clarified wastewater:

Construction cost (million dollars) =

$0.490535Q^{1.10744}$ (4.13)

O&M cost (dollars/day) = $40.9442Q^{.778987}$ (4.14)

where Q represents design capacity measured by millions of gallons per day (mgd).

As pointed out in Chapter II, the long-run cost curve is the envelope of the short-run cost curves. Cost equations (4.5) through (4.8) were estimated by regression analysis from cross-section data, and these cost observations were subject to variations in the age, type, and cost of equipment, the quality of executives as well as the effects from spatial variation in factor prices. Cost equations (4.2) through (4.4) and (4.9) through (4.14) were estimated as the loci of minimum costs by the engineering approach. Therefore, equations (4.1) through (4.14) as used in this study to estimate the wastewater treatment costs give higher cost estimates than the minimum theoretical costs from equation (2.4d).

Assumptions about Cost Increases

In order to estimate the rates of cost increases over time to be used in the calculation of present values, regression analysis was used. In this analysis, we assume that cost index is a function of time, i.e.,

$$\text{Cost index}_t = a + bt + u_t \qquad t = 1966, \ldots, 1973$$

where a and b are parameters to be estimated, and u_t is the disturbance term at time t.

Three different kinds of cost indexes were used in this analysis, they are: sewer construction cost index (SW), sewage treatment plant construction cost index (ST), and consumer price index for residential water and sewerage services (SR).[7] All the September cost index figures from 1966 to 1973 were used for the estimation of parameters a and b, and the results are as follows:

$$\hat{SW}_t = \underset{(1990.00)}{-23567.0} + \underset{(1.0104)}{12.0444t} \qquad R^2 = .9595 \qquad (4.15)$$

$$\hat{ST}_t = \underset{(1585.40)}{-20378.8} + \underset{(0.8050)}{10.4214t} \qquad R^2 = .9654 \qquad (4.16)$$

$$\hat{SR}_t = \underset{(973.204)}{-14604.9} + \underset{(0.4941)}{7.4762t} \qquad R^2 = .9745 \qquad (4.17)$$

where the "hats" on top of SW_t, ST_t, and SR_t represent estimated values, the figures in the parenthesis are estimated standard errors of the parameters, and R^2's are multiple determination coefficients.

Parameter b represents the effect of one unit change in t on the corresponding cost index, hence it can be explained as the annual rate of increase in costs and they were used in equations (3.9) and (3.10).

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[7] These three cost indexes were provided by Advanced Waste Treatment Research Laboratory, Cincinnati, Ohio.

$\hat{b}$ in (4.15) was used in the calculation of sewer construction costs, $\hat{b}$ in (4.16) was used in the claculation of sewage treatment plant construction cost, and $\hat{b}$ in (4.17) was used in the calculation of O&M costs for both sewer and sewage treatment plant. Service lives for pumping stations and wastewater treatment plants were assumed to be 25 years, and for transmission pipelines 50 years. Interest rate was assumed to be 5%.

Potential Sites for Wastewater Treatment Plants

In order to reduce the possible number of potential sites, a computer program written in FORTRAN IV was developed (Appendix I). This computer program calculates

1. the cordinates in miles from the origin (29° 30' parallel of latitude north and 82° 37' 30" meridian of longitude west) for each of the cities of this study (Table 4.6).

2. construction costs and operation and maintenance costs for wastewater treatment plants, transmission pipelines, and pumping stations for each city using equations (4.1) through (4.14), and

3. the transmission cost from each source to the potential sites obtained using equations (2.5) and (2.6).[8] Finally, the program compares the sum of pumping station costs, transmission costs, and regional wastewater treatment costs for each site with the wastewater treatment costs for a completely disaggregated system (i.e., one in which each of the nine cities build their own facilities). If the regional cost is less than or equal to the sum of individual costs, the program prints out the related cost figures.

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[8] w_i represents transmission pipeline cost per mile from city i as calculated from equations (4.2) or (4.4).

Table 4.6 Cordinates of Municipalities in Alachua County in Miles[a]

City	Number[b]	Cordinate	
		East(x)	North(y)
High Springs	1	1.6190	22.4526
Newberry	2	0.8572	10.0476
Archer	3	6.1428	2.0952
Alachua	4	7.9524	20.2380
Gainesville Urban Area	5	18.0476	10.4762
LaCrosse	6	13.1904	23.6666
Micanopy	7	20.9524	0.3810
Waldo	8	27.6190	20.0476
Hawthorne	9	32.5714	6.6190

[a]These cordinates are calculated from the origin 80° 37' 30" longitude West and 29° 30' latitude North in miles.

[b]These numbers will be used later to represent the corresponding cities.

It is assumed that force mains[9] were used as the connecting pipelines between contributing cities and receiving regional plants, and a raw sewage pumping station has been sized to handle the flow at each source.

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[9]Smith and Eilers [1971] indicate that the cost of constructing force mains is not significantly different from the cost of constructing gravity sewers, hence, equation (4.2) may be used to find the construction cost for force mains. However, by a conversation with Mr. Baldwin (Agricultural Engineer), this approach may overestimate the cost of force mains.

The Newton-Raphson method was first used to solve equations (2.5) and (2.6) simultaneously, but this method required too many operations to finish one iteration, hence, it was not used in this study. Instead, an iterative procedure suggested by Kuhn and Kuenne [1962] and by Cooper [1963] was used to solve these two equations for x and y in terms of w_i, x_i, y_i, and d_i:

$$x = \Sigma_i \frac{w_i x_i}{d_i} / \Sigma_i \frac{w_i}{d_i}, \tag{4.18}$$

$$y = \Sigma_i \frac{w_i y_i}{d_i} / \Sigma_i \frac{w_i}{d_i}, \tag{4.19}$$

$$d_i = ((x_i - x)^2 + (y_i - y)^2)^{\frac{1}{2}} \tag{4.20}$$

The value of d_i is recalculated via (4.20) and the procedure repeated until successive differences between values of x and between values of y are negligible. In this study, the initial values of x and y for the calculation of d_i are the weighted average of x_i's and y_i's, respectively. As mentioned by ReVelle et al. [1970] this method has been found to be extremely fast, usually terminating at the global minimum in less than ten iterations, and no problems of lack of convergence have been reported. Therefore, a maximum number of fifty iterations was set and a four-digit accuracy was required for the solution of (x, y). The last (x, y) in the iteration procedure was taken as the solution for (2.5) and (2.6).

A regional treatment plant in this study is defined as one serving more than one city. Let R(.) represent a regional treatment plant which serves the cities represented by the numbers within the parentheses; for example, R(1, 2) is a regional treatment plant that serves cities 1 and 2 (the number for each city has been assigned in Table 4.6). If there is one number within the parentheses, it indicates that a treatment plant serves only one city.

Assuming that d_{1975}, d_{1980}, and d_{1990} were satisfied in years 1975, 1980, and 1990, respectively, Table 4.7 shows the possible sites, capacities, and costs of regional treatment plants, the cities they will serve, and the years they are to be built. There are regional treatment plant sites in the southeast corner of Alachua County other than those presented in Table 4.7 which were not considered because of the lakes and swamps in that area. These sites involve the following regional treatment plants: R(6, 7, 8), R(6, 7, 8, 9), R(7, 8, 9), R(2, 3, 4, 5, 6, 7, 8, 9), and R(1, 2, 3, 4, 5, 6, 7, 8, 9).

Based on the population estimates and wastewater production of 135 gallons per person per day [Loehr, 1968], demands for wastewater treatment and the corresponding treatment costs are calculated. The treatment cost figures in column five in Table 4.7 are the future service values (see next chapter for definition) up to 1990 for the corresponding treatment plants. From these estimates, one finds that (1) high-rate trickling filter plants are cheaper than activated sludge plants,[10] (2) the costs for tertiary treatment processes are higher than the costs of both high-rate trickling filter plants and activated sludge plants.

Assuming that secondary treatment is adequate to meet the requirements, there are several ways to satisfy the demands in the county. If secondary treatment is adequate to meet the requirements the least cost method of treatment is for each city to build a high-rate trickling

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[10]Federal regulation requires a 90% removal of BOD's and SS which high-rate trickling filter plant cannot achieve. However, if tertiary treatment processes were added to this system, the results of trickling filter plant from this study are still valuable. Therefore, the results of trickling filter system were presented and discussed.

Table 4.7 The Potential Sites, Capacities, and Costs of Regional Treatment Plants and the Cities They Served

Cities Served	Cordinate	Time to be Built	Capacity (mgd)	Cost (September 1974 dollars)
I. High-rate Trickling Filter System				
i. with tertiary treatment processes				
(2, 3)	(0.86, 10.04)	1975	.31	2,147,296
(1, 2, 3)	(0.88, 10.07)	1975	.72	4,086,862
(2, 3, 4)	(4.22, 12.34)	1975	.77	4,261,926
(1, 2, 3, 4)	(5.09, 18.82)	1975	1.88	5,816,155
(1, 2, 3, 4)	(4.12, 16.95)	1980	.10	880,555
(1, 2, 3, 4)	(5.32, 18.67)	1990	.28	226,315
ii. without tertiary treatment processes				
none				
II. Activated Sludge System				
i. with tertiary treatment processes				
(1, 2)	(1.62, 22.45)	1975	.59	3,603,283
(2, 3)	(0.86, 10.04)	1975	.31	2,332,163
(8, 9)	(32.57, 6.62)	1975	.28	2,216,676
(1, 2, 3)	(0.88, 10.07)	1975	.72	4,336,789
(1, 2, 3)	(0.86, 10.05)	1980	.08	758,340
(2, 3, 4)	(4.22, 12.34)	1975	.77	4,550,842
(2, 3, 4)	(2.05, 10.12)	1980	.06	657,067
(1, 2, 3, 4)	(5.09, 18.82)	1975	1.18	6,171,936
(1, 2, 3, 4)	(4.12, 16.95)	1980	.10	946,246
(1, 2, 3, 4)	(5.32, 18.67)	1990	.28	235,555
(1, 2, 3, 4, 5, 6, 7, 3)	(18.05, 10.48)	1975	1.69	35,550,720
ii. without tertiary processes				
(1, 2, 3, 4)	(5.09, 18.82)	1975	1.18	3,422,759
(1, 2, 3, 4, 5, 6, 7, 8)	(18.05, 10.48)	1975	1.69	9,605,506

filter plant to meet its demand (Table 4.8). However, if tertiary treatment processes are required to meet the requirements, the results show that High Springs, Newberry, and Archer should cooperate in developing a regional facility if their objective is to minimize cost. The potential site has a cordinate of x = 0.88 and y = 10.07, which is in Newberry, and an estimated regional treatment cost of 4,086,862 September 1974 dollars to satisfy their 1975 demands and to meet their demands in 1980 and 1990 by building individual plants. The other six municipalities should build separate treatment plants to meet their individual demands.

Concluding Remarks

As mentioned in Chapter III, this is a study over time and space. This chapter discussed the consolidation of waste treatment facilities over space for specific points in time, i.e., 1975, 1980, and 1990, respectively. There are other ways that wastewater treatment demands can be satisfied over time. For example, the estimated treatment demands of High Springs are .4090 mgd, .4455 mgd, and .5236 mgd for years 1975, 1980, and 1990, respectively; these demands could be satisfied by building a .5326 mgd treatment plant in 1975. Of course, there are other options. Chapter V brings the time dimension into the optimization process and considers the simultaneous determination of costs over both time and space dimensions.

Since interest is in minimizing costs, combinations over time and space which lead to greater costs than those presented in Table 4.8 need not be considered. Therefore, the results of Chapter V help to narrow the search for an optimal county solution.

Table 4.8 Possible Options for Satisfying County's Wastewater Treatment Demands and Associated Costs, 1975 to 1990[a]

Option	Total Cost for County
I. Without Tertiary Processes	
i. high-rate trickling filter system	
$\sum_{i=1}^{9} R(i)$	12,276,820
ii. activated sludge system	
$R(1, 2, 3, 4) + \sum_{i=5}^{9} R(i)$	14,464,670
$R(1, 2, 3, 4, 5, 6, 7, 8) + R(9)$	14,550,152
II. With Tertiary Processes	
i. high-rate trickling filter system	
$R(1, 2, 3) + \sum_{1=4}^{9} R(i)$	44,589,425
$R(1) + R(2, 3, 4) + \sum_{i=5}^{9} R(i)$	44,590,757
$R(1) + R(2, 3) + \sum_{i=4}^{9} R(i)$	44,765,688
ii. activated sludge system	
$R(1, 2, 3) + \sum_{i=4}^{7} R(i) + R(8, 9)$	46,719,711
$R(1) + R(2, 3) + \sum_{i=4}^{7} R(i) + R(8, 9)$	46,986,390
$R(1, 2) + \sum_{i=3}^{7} R(i) + R(8, 9)$	47,015,999
$R(1, 2, 3, 4) + \sum_{i=5}^{7} R(i) + R(8, 9)$	45,698,220
$R(1, 2, 3, 4, 5, 6, 7, 8) + R(9)$	46,454,733
$R(1) + R(2, 3, 4) + \sum_{i=5}^{7} R(i) + R(8, 9)$	46,698,720

[a]Assuming that d_{1975}, d_{1980}, and d_{1990} were satisfied in years 1975, 1980, and 1990, respectively.

CHAPTER V
CAPACITY EXPANSION SCHEME

Investment Over Time

When a firm experiences a growing demand for its output and makes investments aimed at increasing its capacity in existing lines of activity, the outlays are called induced investments. When, on the other hand, the firm diversifies into new lines of activity, the capital investments involved are referred to as autonomous investments [Dernburg and McDougall, 1968]. This study deals only with induced investments of wastewater treatment facilities.

The simplest feedback theory of how induced investment takes place is called the acceleration principle. This principle holds that the rate at which a firm invests in new, as opposed to replacement, equipment is a linear function of the rate of change of output. Suppose a wastewater treatment plant has a capacity of 1.0 mgd, and is operating at that capacity. Assuming that the only way to increase treatment capacity is to add more capacity, then as demand increases capacity must be increased in direct proportion.

The acceleration principle assumes that capacity is well defined and that when it is reached such alternatives as overtime, subcontracting, and back ordering are not available. The principle purports to explain only new investment or net investment and also assumes that the firm is able to obtain the funds to finance the indicated expansion.

When demand is constant the firm's investment may be confined to replacement of its existing capacity, although if this was not being fully utilized the firm might actually neglect replacement. While the acceleration principle provides a first indication, effective implementation of an expansion program requires considerably greater insight.

Capacity is not a particularly well-defined concept in most firms. There is a gradual growth in unfilled orders and overtime, shifts are added, and any slack or hidden capacity comes into use. Thus management has several alternatives to capacity expansion. It can use inventories as a demand buffer to insulate to some extent the steady operation of production facilities from changes in the market. Negative inventories or back orders are a useful means of meeting what appear to be temporary increases in demand. The capacity of existing facilities can also be extended by working overtime or expanding the working force. Sometimes capacity can be expanded by subcontracting part of the production process to others and effectively buying rather than making some of the required output.

In the planning and designing of a wastewater treatment facility for a town, city, or an area where wastewater treatment requirements are expected to increase with time, the questions as to the initial size of the treatment plant and the timing of capacity additions and/or replacements over the period of study or time horizon have to be answered in the context of an optimal staging policy. Such a policy is affected by the wastewater treatment requirement and its growth rate; the rates of interest and inflation; the cost of the treatment plant and its operation and maintenance; the load factor, service life, and expected salvage value of the treatment plant; and the staging efficiency of the system to be designed.

Incremental savings in construction and operation and maintenance costs due to economies of scale make it desirable to bear the cost of overcapacity until demand catches up. A major decision variable in public and private wastewater treatment plant staging policy is the amount of excess capacity to be built initially into a new system and the staging of capacity additions and/or replacement (as the old plants become uneconomical to run, being past their useful service life) to meet demands increasing with time.

For example, the vertical axis in Figure 5.1 represents the long-run average construction cost for wastewater treatment, and the horizontal axis represents the demand for wastewater treatment capacity. Q_{1975} and Q_{1980} represent the required capacities in 1975 and 1980 respectively; LL is the long-run average construction cost curve. Assume there are two choices to chose from, i.e., to build a single plant with capacity Q_{1980} in 1975, or to build one plant with capacity Q_{1975} in 1975 and another one with capacity $Q_{1980} - Q_{1975}$ in 1980. The difference in construction costs represented by present value is

$$D_c = ocdj - obeh - oafg \frac{(1 + \lambda)^5}{(1 + i)^5} , \qquad (5.1)$$

where oa = oc − ob, λ represents rate of inflation in construction cost, i represents interest rate, and D_c represents the difference in construction costs between these two options. If $D_c > 0$, then there is a saving in construction cost, if $D_c < 0$, then there is a loss in the two-plant option. However, the choice between a single-plant option and two-plant option depends not only on construction costs but on operation and

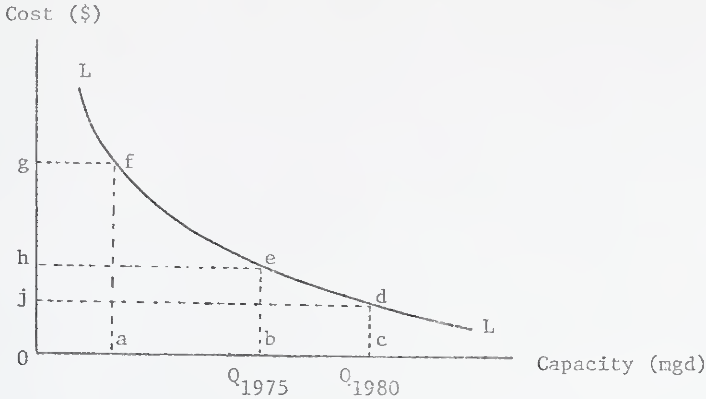

Figure 5.1 Long-run Average Construction Cost Curve

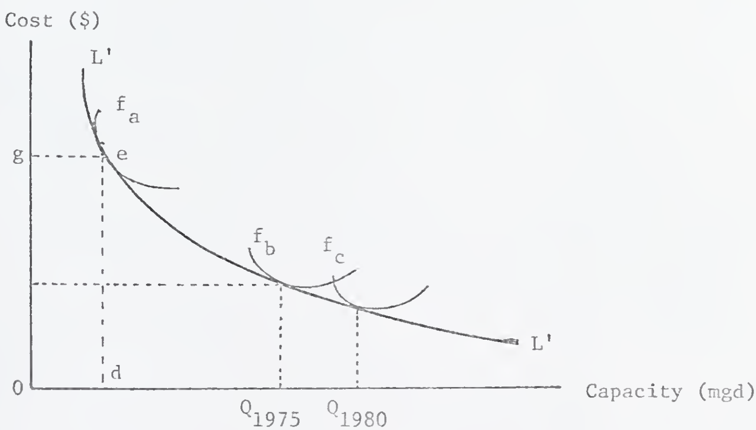

Figure 5.2 Average Operation and Maintenance Cost Curve

maintenance (O&M) costs also. In Figure 5.2, L'L' represents long-run average O&M cost curve, which is the envelop of short-run cost curves f_a, f_b, f_c, for capacities $Q_{1980} - Q_{1975}$, Q_{1975}, and Q_{1980}, respectively, od equals the difference between Q_{1975} and Q_{1980}. The present values of O&M cost for the two options mentioned above follow.

$$\text{Single-plant option:}\quad D_1 = \text{present value of} \int_{Q_{1975}}^{Q_{1980}} Q \cdot f_c \, dQ \tag{5.2}$$

$$\text{Two-plant option:}\quad D_2 = \text{present value of} \int_{Q_{1975}}^{Q_{1979}} Q \cdot f_b \, dQ + \text{Odeg} \tag{5.3}$$

where f_c and f_b are functions of operating capacity Q. Let

$$D_{om} = D_1 - D_2 \tag{5.4}$$

then if $D_c + D_{om}$ is negative, the single-plant option will be chosen, otherwise the two-plant option will be chosen.

For each potential site the model may be stated as

Model 1

$$\text{Min} \quad FT_{1975}(Q_{1975}) + FT_{1980}(Q_{1980}) + FT_{1990}(Q_{1990})$$

$$\begin{aligned} \text{s.t.} \quad & Q_{1975} && \geq d_{1975} \\ & Q_{1975} + Q_{1980} && \geq d_{1980} \\ & Q_{1975} + Q_{1980} + Q_{1990} && \geq d_{1990} \\ & Q_{1975},\ Q_{1980},\ Q_{1990} && \geq 0 \end{aligned}$$

where $FT_t(Q_t)$'s are total cost functions of treatment facilities in terms of present value of plants to be built at time t with design capacity Q_t, and d_t's are scalars as demand for wastewater treatment at time t, where t = 1975, 1980, and 1990.

As mentioned above, $FT_t(Q_t)$ for t = 1975, 1980, 1990, includes construction costs as well as O&M cost. The O&M cost as mentioned in equations (5.2) and (5.3) involves short-run cost functions. There are several points about short-run cost functions that should be discussed. First, as shown in Figure 5.3, L'L' represents a long-run cost curve, and f_c represents a conventional short-run cost curve. To the left of point g, short-run average cost increases as Q decreases. This may be explained as the indivisibility of management, production factors, and the like. The decrease in Q will not decrease the quality of effluent. However, to the right of point g, can one expand Q without reducing the quality of effluent? Or, can one expand Q by working overtime, adding more shifts, or increasing the inventory of raw sewage? The capacity of a treatment plant is measured by a rate (e.g., million gallons per day) and the possibility of expanding treatment capacity Q beyond the design capacity without reducing the quality of effluent may not exist. Hence, the segment of the short-run cost curve to the right of point g may not exist if the quality of effluent has to be maintained.

Second, there are very few studies about short-run costs of wastewater treatment, and therefore it is difficult, if not impossible, to find short-run cost functions with the capacities needed in this study. As a proxy, long-run O&M cost functions were used. There are shortcomings with this approach. For example, if a treatment plant is to be build with capacity Q_{1980} in 1975, one should use f_c to estimate the O&M costs from 1975 through 1980; however, there is no information abour f_c. Therefore, if L'L' is used to estimate O&M cost with capacity Q_{1980}, it is difficult to determine if the cost has been over- or underestimated without knowing f_c since there is no information about the difference between ojgh and oacd.

In this study, each treatment, transmission, or pumping facility has been assumed to operate at its design capacity. The reasons are

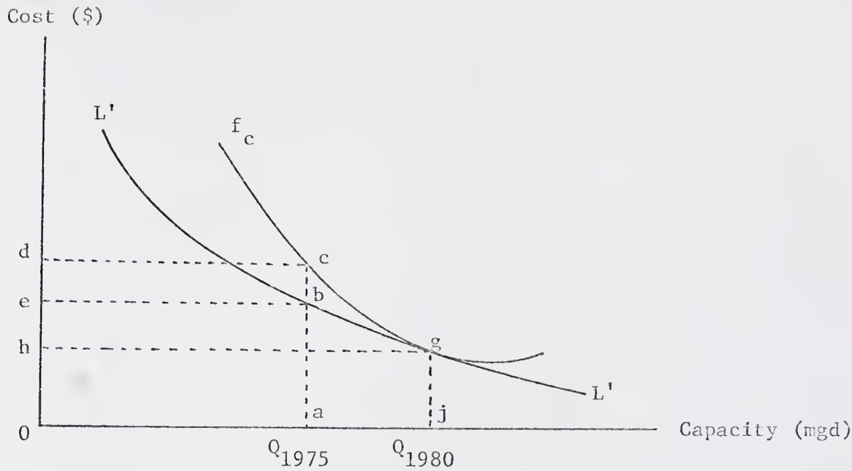

Figure 5.3 Operation and Maintenance Cost over Time

that 1) there is not enough information about short-run cost functions, especially for advanced treatment processes, 2) this study was for planning purposes and emphasis was placed on the long-run effect, and 3) in most cities the differences in demands for wastewater treatment over time are not large; therefore, the differences between long-run cost estimates under design capacity and short-run cost estimates under capacity in use may not be substantial.

In this study, interest is in satisfying the demands for wastewater treatment in 1975, 1980, and 1990. The demand functions for wastewater treatment over time can be considered as step functions rather than as continuous functions. One example is shown in Figure 5.4, where d(t) represents a continuous function, and d'_{1975}, d'_{1980}, and d'_{1990} are segments of a step function. One of the disadvantages of using step functions for wastewater treatment demands is that one may underestimate the quantity of demand toward the end of each time period, but if each time period is not large, this underestimation will not be serious. The advantage of using step functions is that it simplifies the staging process. For example, instead of considering Model 2 in this study, we consider Model 1 which when compared to Model 2 is easier to solve.

Model 2

$$\text{Min} \quad \sum_{t=1975}^{1990} FT_t(Q_t)$$

$$\text{s.t.} \quad Q_{1975} \geq d_{1975}$$

$$\sum_{t=1975}^{t''} Q_t \geq d_{t''} \qquad \text{for all } t'' \leq 1990$$

$$Q_t \geq 0, \ 1990 \leq t \leq 1975$$

where FT, Q, and d are as defined in Model 1.

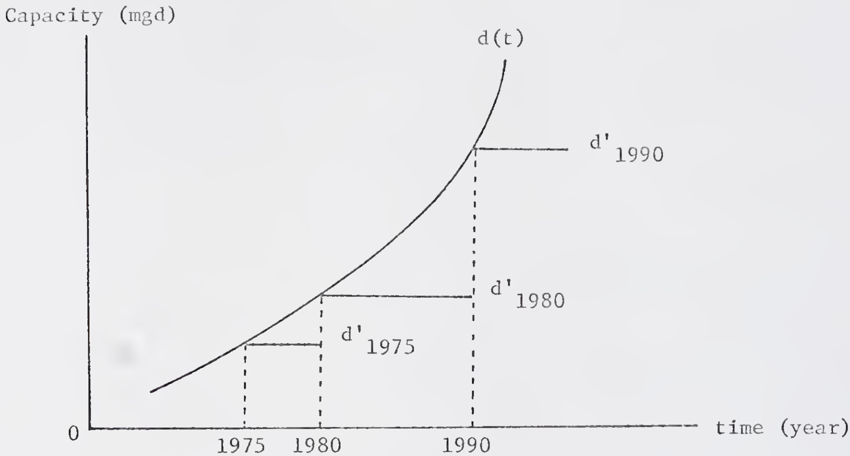

Figure 5.4 Demand for Wastewater Treatment over Time

The difference between Model 1 and Model 2 is mainly in the time variable, t. In Model 2, t is a continuous variable; therefore the two constraints in the model are not well defined. Unless one can split the time variable into some finite segments, that is to say t is a step function rather than a continuous function, one may not be able to solve Model 2.

Let $d_{1975} < Q_{1975} < d_{1980}$, and $FT_{1975}(x)$, $FT_{1980}(x)$ be functions in present value for years 1975 and 1980 respectively, and x be the design capacity. If one can show that

$$\begin{aligned} & FT_{1975}(Q_{1975}) + FT_{1980}(d_{1980} - Q_{1975}) \\ > \; & FT_{1975}(d_{1980}) \end{aligned} \tag{5.5}$$

then the capacities between d_{1975} and d_{1980} for year 1975 do not have to be considered. This is to say, it is more expensive to build two treatment plants with capacities Q_{1975} and $d_{1980} - Q_{1975}$ in 1975 and 1980, respectively. If this is true, the problem is simplified to choosing the minimum cost plan from the following options.

Table 5.1 Reference Numbers for Time Options in Alachua County, Florida, 1975 to 1990

Options	Demand for Wastewater Treatment	To Be Satisfied in Year(s)
1	d_{1975}	1975
	$d_{1980} - d_{1975}$	1980
	$d_{1990} - d_{1980}$	1990
2	d_{1980}	1975
	$d_{1990} - d_{1980}$	1990
3	d_{1980}	1975
	$d_{1990} - d_{1980}$	1980

Table 5.1 (Cont.)

Options	Demand for Wastewater Treatment	To Be Satisfied in Year(s)
4	d_{1975}	1975
	$d_{1990} - d_{1975}$	1980
5	d_{1990}	1975

Now, split FT into construction cost, CC, and Operation and maintenance cost, OC, and consider construction cost only in the following inequality:

$$CC_{1975}(Q_{1975}) + CC_{1980}(d_{1980} - Q_{1975}) > CC_{1975}(d_{1980}) \tag{5.6}$$

where $d_{1975} < Q_{1975} < d_{1980}$. If inequality (5.6) holds, and if only the construction cost is considered, it is more economical to build a plant with capacity d_{1980} in 1975 than any other plan which can meet the treatment requirement, d_{1980}, in 1980. If inequality (5.6) holds, one should only consider the tradeoff between the savings in capital by meeting d_{1980} in 1975 with the losses of O&M cost in excess capacity. In other words, one only has to consider three capacities, d_{1975}, d_{1980}, and d_{1990}, in year 1975, not a continuum on the interval $[d_{1975}, d_{1990}]$. The following lemma is used to prove that (5.6) holds

<u>Lemma</u> Suppose $f(x) = (1 + x^{\beta}) - (1 + x)^{\beta}$ is continuous on $(0,\infty)$, $f'(x)$ exists at some point $x \varepsilon (0,\infty)$, and $0 < \beta < 1$, then $x^{\beta} > (1 + x) - 1$.

Proof:
$$f(0) = (1 + 0)^{\beta} - (1 + 0)^{\beta} = 0 = \lim_{x \downarrow 0} f(x)$$
$$f'(x) = \beta x^{\beta-1} - \beta(1 + x)^{\beta-1}$$
$$= \beta[(\frac{1}{x})^{1-\beta} - (\frac{1}{1 + x})^{1-\beta}]$$

Now $(\frac{1}{x})^{1-\beta} - (\frac{1}{1+x})^{1-\beta} > 0$, for all $x > 0$, since $x < 1 + x$. Therefore, $\frac{1}{x} > \frac{1}{1+x}$, and since $1 - \beta > 0$, $(\frac{1}{x})^{1-\beta} > (\frac{1}{1+x})^{1-\beta}$. Hence, $f'(x) > 0$, which implies $f(x)$ is an increasing function and $\lim_{x \downarrow 0} f(x) = 0$. In other words,

$$\begin{aligned} f(x) &= (1 + x^{\beta}) - (1 + x)^{\beta} > 0 \qquad &\text{for } x > 0 \\ &= 0 \qquad &\text{for } x = 0 \end{aligned}$$

where $0 < \beta < 1$ and $x \geq 0$. Therefore, $1 + x^{\beta} > (1 + x)^{\beta}$, or $x^{\beta} > (1 + x)^{\beta} - 1$.

All the construction cost curves except the one for transmission pipelines are of form

$$CC_t(Q_t) = \alpha_t Q_t^{\beta},\ Q > 0,\ 0 < \beta < 1, \text{ and } t\varepsilon[1975, 1990]$$

and $\alpha_t > \alpha_{t'}$ if $t > t'$ because the rate of inflation is greater than the rate of interest. If (5.6) holds, the following will hold:

$$\begin{aligned} &\alpha_{1975} Q^{\beta}_{1975} + \alpha_{1980}(d_{1980} - Q_{1975})^{\beta} \\ &> \alpha_{1975}(d_{1980})^{\beta} \end{aligned} \tag{5.7}$$

Divide both sides of (5.7) by α_{1975} to obtain,

$$Q^{\beta}_{1975} + \gamma(d_{1980} - Q_{1975}) > d^{\beta}_{1980}$$

where $\gamma = \frac{\alpha 1980}{\alpha_{1975}} > 1$, or

$$\gamma(d_{1980} - Q_{1975})^{\beta} > d^{\beta}_{1980} - Q^{\beta}_{1975} \tag{5.8}$$

where $d_{1980} > Q_{1975} > 0$, and $0 < \beta < 1$. Inequality (5.8) can be rewritten as:

$$\gamma[\frac{d_{1980}}{Q_{1975}} - 1]^{\beta} > (\frac{d_{1980}}{Q_{1975}})^{\beta} - 1 \tag{5.9}$$

Therefore, if $[\frac{d_{1980}}{Q_{1975}} - 1]^{\beta} > (\frac{d_{1980}}{Q_{1975}})^{\beta} - 1$, inequality (5.6) holds.

By lemma, we have $x^{\beta} > (1 + x)^{\beta} - 1$ if $x > 0$, and $0 < \beta < 1$, let $x = (\frac{d_{1980}}{Q_{1975}}) - 1 > 0$, then $\frac{d_{1980}}{Q_{1975}} = 1 + x$. Hence, by the lemma inequality (5.9) holds. Therefore, given the estimated cost functions all one has to do is to choose the minimum cost plan from the five options mentioned above.

Future Service Value of Treatment Facilities

In this study, the service lives for treatment plants and pumping stations are assumed to be 25 years, and for transmission pipelines 50 years. The five options mentioned in the previous paragraph involve building treatment plants with different capacities in different years. In order to make a comparison among the costs of these five options, the cost of unused services of each option after 1990 should be subtracted from the total cost.

From an economic point of view, a capital asset is nothing but a store or reservior of valuable future services, from which alone the value of the asset derives. We say "future services" because they can be used up only over a period of time. They are deferred benefits. If these services were valued at par, this is to say, at what they will eventually be worth when realized, the capital value of the asset would, of course, equal their sum. But a business enterprise does not knowingly buy future services at par if profits are to exist. To earn profits a firm must buy the asset for less than its services will eventually be worth, the profit over the asset life as a whole being the excess of these service values over the acquisition and use costs. The capital value of the asset, in other words, is the discounted value, or present worth, of these service values, the latter in turn being the amount available for capital recovery and profit combined.

It is a matter of common observation that the services of capital assets tend to become less and less valuable as time goes on. The majority of the assets require during their service lives a flow of maintenance expenditures, which as a rule rises irregularly with age and use. Most of them suffer a progressive deterioration in the quality or the adequacy of their service. Moreover, in dynamic technology they are subject to the competition of improved substitutes, so that the quality of their service declines relative to the available alternatives even when it does not deteriorate absolutely.[1] All of these factors--rising operation costs, impaired service quality or adequacy, and improved alternatives--combine to reduce the value of the service as the asset ages.

In practice, the future service value of an asset has to be estimated. Such estimates are quite common in the valuation of real estate, where annual service values are projected and discounted into capital value. It must be admitted that they are not much employed in the valuation of other types of property.

With the exception of land, the productive facilities of industry are wasting assets and are depreciated with time and use until the capatal embodied in the facilities is exhausted over their productive service lives. The worth of the asset to the owner at any given point is what he could afford to pay for it in competition with the various alternatives then available, if he did not already have it. So long as he elects to hold the asset, it may be presumed that this worth is above

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[1]This deterioration in the quality of service, both absolutely and relative to current alternatives, is reflected in a general tendency to reduce the intensity or continuity of use of the asset as time goes on.

resale value. It may also be presumed that the decline therein since the asset was acquired has been less than the decline from original to resale value.

Costs make up the depreciation base for purchased assets. In setting up a depreciation schedule a firm must establish a useful life and salvage value of the asset in question. The most common methods of depreciation are straight-line, declining-balance, sum of the digits, and unit-of-production or service [Dougall, 1973, p. 474]. Since the probable loss of capital value is decidedly concentrated in the early part of life, the straight-line writeoff is not a completely satisfactory method of depreciation for productive equipment. Any realistic allocation procedure should get rid of at least one half of the initial value over the first third of the service life and at least two-thirds over the first half. The straight-line method is perhaps less objectionable for buildings and structures than for equipment [Terborgh, 1954, pp. 37, 47].

In this study, wastewater treatment facilities are long-term investments, and a straight-line method was used to calculate the depreciation of facilities. The undepreciated balance of the assets was discounted back to present value for each of the options mentioned above and subtracted from the present value of costs.

Construction costs, less discounted salvage value divided by the estimated years of life, produced (for each type of fixed asset) a uniform depreciation expense each year. The salvage values for treatment facilities in this study were assumed negligible. The present value of future costs included both construction and O&M costs.

As mentioned in Chapter III, this study tries to find the least cost option to satisfy the wastewater treatment demands for the nine cities in Alachua County, subject to five constraints.

By inequality (5.6), it is obvious that if cost curves are of form

$$CC_t(Q_t) = \alpha_t Q_t^{\beta} \quad Q > 0,\ 0 < \beta < 1, \text{ and } t \varepsilon [1975, 1990]$$

there is no need to transport waste to more than one location for treatment. All the cost curves used in this study but two--one for transmission pipelines and one for ammonia stripping--are of this form, and a study by Smith and Eilers [1971] shows that there are economies of scale existing in transmission pipeline construction cost, which suggests this cost curve has the same form. Ammonia stripping is a very small part of the total cost for the facilities studied here so no waste was transported to more than one location for treatment.

A computer program was developed to scan through all the possible ways of satisfying wastewater treatment demands of the nine cities in Alachua County. This computer program consists of one main program, four subroutines, and two functions, they are MAIN, GRAVTY, TRT, COST, ZERO, TRM, and PMG, respectively (see Appendix I). Their individual functions follow:

MAIN:
1. To read city cordinates, population figures, and calculate wastewater treatment demands over time;
2. To calculate construction costs as well as operation and maintenance costs of pipelines per mile, pumping stations, and treatment costs (both secondary and tertiary treatment) for each city and time of interest according to the needs of each city, and to print out the results. The printout includes wastewater treatment demands, population figures, and all the needed cost figures over time;
3. To generate a combination of cities and send it to subroutine GRAVTY for regionalization analysis.

GRAVTY: 1. Using the combination provided by MAIN to find out the potential site for regional treatment and to calculate transmission costs for regional treatment;

2. To sum up the individual treatment costs of the cities in the combination and to calculate regional total cost;

3. To compare the sum of individual treatment cost and regional total cost. If regional total cost is lower, print out the cordinates of potential treatment site, regional treatment costs, transmission costs, pumping station costs, sum of individual treatment costs, and the distance from each city in the combination to the potential site. If the sum of individual costs is lower, return to step 3 in MAIN to get a new combination, until all the possible combinations are exhausted.

TRT, TRM, PMG: To provide cost figures of treatment, transmission pipeline, and pumping station, respectively, which are required by MAIN, GRAVTY, and COST.

COST: Using the combination provided by MAIN to screen out the required information about costs and send it to GRAVTY for further calculation.

ZERO: To initialize some of the variables in COST.

There are 491 potential sites for each time option, five time options, two kinds of secondary treatment, and three tertiary treatment processes. The program is instructed to choose one secondary treatment with and without tertiary treatment processes, one time option, and one potential site at a time to calculate cost figures, and give answers to the feasibility of regional treatment until all the possible combinations of treatment types, time options, and potential sites are exhausted. This is a brute-force search for the solution of the optimization model mentioned in Chapter III.

Minimum Cost Option for Wastewater Treatment

In the last chapter it was shown that if only secondary treatment facilities are required a regional wastewater treatment plant is not needed. In this case individual high-rate trickling treatment plants will give minimum cost option provided that d_{1975}, d_{1980}, and d_{1990} are satisfied in years 1975, 1980, and 1990, respectively. However, under the same scheme, if tertiary treatment processes are required, there is one regional treatment plant site which has a higher gain in economies of scale than the losses in pumping and transmission pipelines, and has a minimum cost among the nine options under considerations, and this regional treatment plant has a capacity which satisfies the 1975 demands for wastewater treatment of three cities in 1975.

The same procedures in the previous chapter were used to scan through all the combinations of time, treatment types, and combinations of cities to meet the demand for each of the time options mentioned in Table 5.1.

To simplify the discussion, Table 5.2 shows all the possible regionalization options, and a number is assigned to each. In the following discussion or representation, instead of repeating the constituents of these options, reference numbers will be used. For example, regional option 11 represents the plan which consists of a regional treatment plant which serves cities 1 through 8 and a single plant serving city 9.

Table 5.3 shows the seven ways of satisfying demands over 1975, 1980, and 1990. Present value of future cost of possible regional treatment plants, cities to be served, and capacities to be built by types are also presented. For example, if d_{1975} is satisfied in 1975, there are four possible regional high-rate trickling filter regional plants with tertiary processes, seven possible regional activated sludge plants with tertiary processes, and two possible regional activated sludge plants without tertiary treatment processes. Present value of costs up to 1990 in terms of September 1974 dollars are shown in columns

Table 5.2 Reference Numbers for Regional Wastewater Treatment Options in Alachua County, Florida, 1975 to 1990

Regional Wastewater Treatment Options	Reference Number
$\sum_{i=1}^{9} R(i)$	1
$R(1) + R(2,3) + \sum_{i=4}^{9} R(i)$	2
$R(1, 2, 3) + \sum_{i=4}^{9} R(i)$	3
$R(1) + R(2, 3, 4) + \sum_{i=5}^{9} R(i)$	4
$R(1, 2, 3, 4) + \sum_{i=5}^{9} R(i)$	5
$R(1, 2) + \sum_{i=3}^{7} R(i) + R(8, 9)$	6
$R(1) + R(2, 3) + \sum_{i=4}^{7} R(i) + R(8, 9)$	7
$R(1, 2, 3) + \sum_{i=4}^{7} R(i) + R(8, 9)$	8
$R(1) + R(2, 3, 4) + \sum_{i=5}^{7} R(i) + R(8, 9)$	9
$R(1, 2, 3, 4) + \sum_{i=5}^{7} R(i) + R(8, 9)$	10
$R(1, 2, 3, 4, 5, 6, 7, 8) + R(9)$	11

Table 5.3 Present Value of Costs of Alternative Regional Treatment Plants for Alachua County, Florida, 1975, 1980, and 1990[a]

Regional Treatment Plant	Activated Sludge System		High-rate Trickling Filter System	
	tertiary processes		tertiary processes	
	with	without	with	without
1. d_{1975} is satisfied in 1975				
R(2, 3)	2,232,163	---	2,147,296	---
R(1, 2)	3,603,283	---	---	---
R(8, 9)	2,216,676	---	---	---
R(1, 2, 3)	4,336,789	---	4,086,862	---
R(2, 3, 4)	4,550,842	---	4,261,926	---
R(1, 2, 3, 4)	6,171,936	3,422,759	5,816,155	---
R(1, 2, 3, 4, 5, 6, 7, 8)	35,550,720	9,605,506	---	---
2. $d_{1980} - d_{1975}$ is satisfied in 1980				
R(1, 2, 3)	758,340	---	---	---
R(2, 3, 4)	657,067	---	---	---
R(1, 2, 3, 4)	946,246	---	880,555	---
3. $d_{1990} - d_{1980}$ is satisfied in 1990				
R(1, 2, 3, 4)	226,315	---	235,555	---
4. $d_{1990} - d_{1980}$ is satisfied in 1980				
R(2, 3)	618,276	---	---	---
R(1, 2, 3)	1,260,849	---	1,273,937	---
R(2, 3, 4)	1,426,352	---	---	---
R(1, 2, 3, 4)	1,859,144	---	1,742,912	---
5. d_{1980} is satisfied in 1975				
R(1, 2)	3,824,863	---	---	---
R(2, 3)	2,495,646	---	2,301,272	---
R(8, 9)	2,297,853	---	---	---
R(1, 2, 3)	4,650,832	---	4,357,962	---
R(2, 3, 4)	4,773,810	---	4,474,878	---
R(1, 2, 3, 4)	6,506,944	3,558,569	6,137,994	---
R(1, 2, 3, 4, 5, 6, 7, 8)	40,885,104	---	---	---

Table 5.3 (Cont.)

Regional Treatment Plant	Activated Sludge System		High-rate Trickling Filter System	
	tertiary processes		tertiary processes	
	with	without	with	without
6. d_{1990} is satisfied in 1975				
R(1, 2)	4,327,626	---	---	---
R(2, 3)	2,830,965	---	2,617,682	---
R(8, 9)	2,478,977	---	---	---
R(1, 2, 3)	5,272,472	---	4,952,246	---
R(2, 3, 4)	5,516,895	---	5,185,699	---
R(1, 2, 3, 4)	7,474,954	4,052,585	7,068,858	---
R(1, 2, 3, 4, 5, 6, 7, 8)	53,032,960	---	---	---
7. $d_{1990} - d_{1975}$ is satisfied in 1980				
R(1, 2)	1,256,987	---	---	---
R(2, 3)	872,681	---	---	---
R(1, 2, 3)	1,594,391	---	1,489,681	---
R(2, 3, 4)	1,681,106	---	1,571,759	---
R(1, 2, 3, 4)	2,244,183	---	2,110,057	---

[a]All costs are in September 1974 dollars.

2 to 5 in Table 5.3. Other possibilities and their costs up to year 1990 are also shown in Table 5.3.

In order to find the least cost combination these cost figures (Table 5.3) were assembled with other individual treatment costs to estimate county total costs. All the regional plants shown in Table 5.3 have lower costs than the sum of the costs of individual plants for the cities each regional plant serves. Therefore, for the five time options mentioned in Table 5.1, regional treatment plants were chosen first, and the discrepancies over time and over space were filled by individual plants.

Table 5.4 shows all the county total cost figures according to time options and regional wastewater treatment schemes. Cost figures are discounted present values of all costs up to 1990. From these figures, one finds that time option 2, i.e., the option to satisfy d_{1980} in 1975 and $d_{1990} - d_{1980}$ in 1990, has the lowest cost for both systems and for all the treatment schemes. And as before, the activated sludge system has a higher cost than the high-rate trickling filter system.

Though simpler and cheaper to operate, the typical trickling filter plant is being used less and less on domestic sewage in North America due to the fact that it does not achieve the percent removal of organic material that an activated sludge plant does. The least cost method thus depends on the required quality of the effluent. Typical effluents from trickling filter plants treating domestic wastes have BOD's and SS usually greater than 20 mg per liter. Typical removal efficiencies for both BOD and SS are in the area of 80%. Activated sludge plant effluents have BOD's and SS between 10 and 20 mg per liter and removal efficiencies in the area of 90%.

Table 5.4 Present Value of Cost of Alachua County Wastewater Treatment by Time Options and by Regional Wastewater Treatment Options, 1975 to 1990[a]

Regional Wastewater Treatment Options[b]	Time Options[c]				
	1	2	3	4	5
I. Without tertiary treatment processes					
i. high-rate trickling filter system					
1	12,276,820	10,835,623	16,631,561	16,219,685	14,685,224
ii. activated sludge system					
5	14,465,670	12,768,164	19,324,618	19,162,424	16,902,957
11	14,550,152	12,951,232	19,507,686	18,946,951	17,105,595
II. With tertiary treatment processes					
i. high-rate trickling filter system					
2	44,765,688	42,548,342	55,221,302	54,452,855	52,438,727
3	44,589,425	42,366,611	55,027,933	54,256,641	52,218,817
4	44,590,757	42,362,230	55,026,180	53,520,527	51,550,200
ii. activated sludge system					
6	47,015,999	44,489,214	58,023,694	57,196,318	54,780,531
7	46,986,390	44,456,448	57,980,534	57,149,740	54,741,158
8	46,719,711	44,143,900	57,620,161	56,786,834	54,388,395
9	46,673,720	44,138,483	57,623,055	56,786,215	54,387,249
10	45,698,220	43,423,973	56,293,749	55,851,144	53,551,088
11	46,454,733	44,067,336	57,581,816	56,635,810	54,455,944

[a]All costs are in September 1974 dollars.

[b]See Tables 5.2 and 5.3 for interpretation of number representing a treatment option.

[c]See Table 5.1 for a definition of time option.

Hence, if the required quality of secondary effluent is set at 90% removal, a trickling plant will not achieve this level of removal, and an activated sludge plant would be required to provide the least cost method of treating wastewater. The results in Table 5.4 show that if only secondary treatment is required, the least cost method suggests that the cities of High Springs, Alachua, Archer, and Newberry should cooperate to build a regional treatment plant with cordinate x=5.02, y=18.77 in 1975 to satisfy their 1980 demands. Added demands in 1990 were satisfied in the solution by the construction of individual plants. For the other five cities, time option 2 was used to satisfy their demands by building individual activated sludge plants for each. However, if tertiary treatment processes are required, one would build two regional activated sludge plants, one for the cities of High Springs, Alachua, Archer, and Newberry with cordinate x=5.02, y=18.77, and one for Waldo and Hawthorne with cordinate x=32.57, y=6.62, in 1975 to satisfy the 1980 demands of the six cities. Added demands in 1990 were satisfied in the solution by the construction of individual plants. For the other cities--Gainesville Urban Area, LaCrosse, and Micanopy--time option 2 and individual activated sludge plants were used to satisfy demands.

If the required quality of secondary effluent is set at 80% removal, a trickling filter plant will provide the least cost method (Table 5.4) of treating wastewater. The solution suggests that each city should built its own high-rate trickling filter plant according to time option 2. However, if tertiary treatment processes are required, one would build a regional high-rate trickling filter plant for the cities of Alachua, Archer, and Newberry with cordinate x=4.02, y=12.03

in 1975 to satisfy the 1980 demands of the three cities. Added demands for these three cities in 1990 were satisfied in the solution by the construction of individual plants. For the other six cities--High Springs, the Gainesville Urban Area, LaCrosse, Micanopy, Waldo, and Hawthorne--time option 2 and high-rate trickling filter plants should be used to satisfy the demands.

Figure 5.5 shows the locations of the regional activated sludge treatment plants and the lengths of pipelines from the cities to these two sites. Figure 5.6 does the same for the regional trickling filter treatment plant. Tables 5.5 and 5.6 show the details of the minimum cost schemes for secondary treatment and advanced treatment, respectively. The figures in parentheses are the corresponding treatment capacities in mgd to be built. The difference in treatment capacities between secondary treatment and tertiary treatment in the Gainesville Urban Area is due to the fact that the Gainesville Urban Area has secondary treatment plants with capacity 9.5 mdg, but has no tertiary treatment facilities. Therefore, if tertiary treatment is required, the facilities should be large enough to handle all the wastewater generated in this area.

The results shown in Tables 5.5 and 5.6 were calculated under the assumption that one can build a treatment plant as small as one likes. However, this assumption may not be realistic. If one suspects that the capacity, for instance, required for Micanopy in 1990 under time option 2 is too small to be practical, then time option 5 would provide second best solutions. The present values of cost for each city or regional plant for both secondary treatment and secondary treatment with tertiary processes for time option 5 are presented in Table 5.7. The conclusions are still the same as those from time option 2, except the cost figures

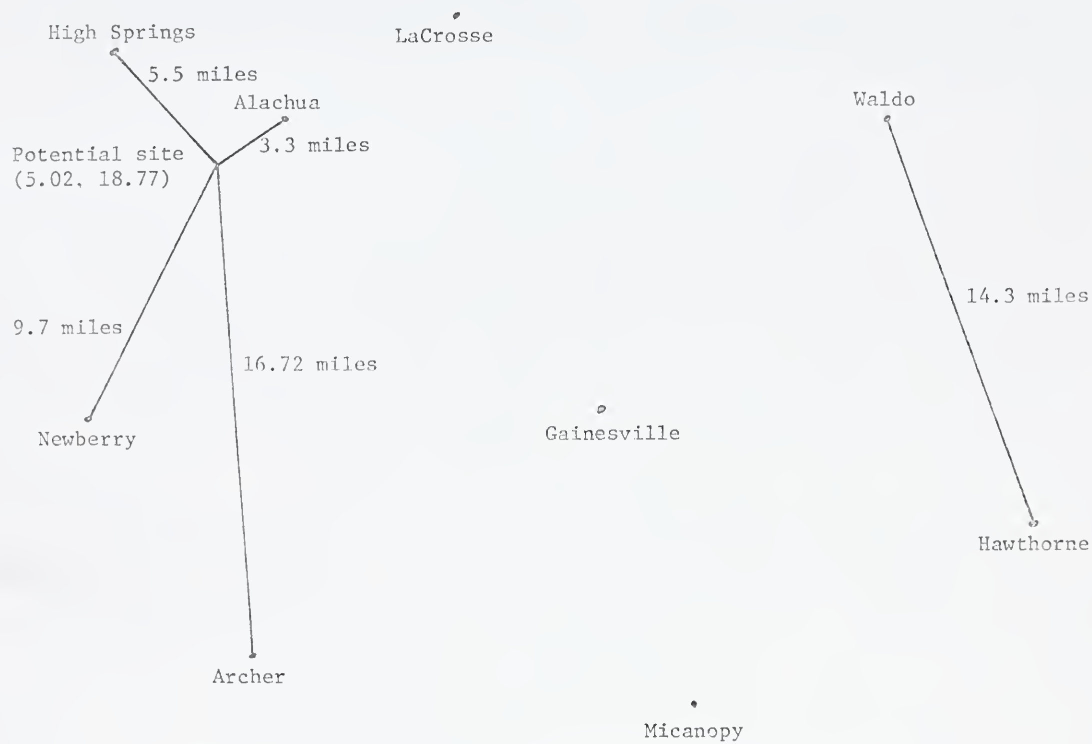


Figure 5.5 Relative Location of Potential Regional Treatment Sites for Activated Sludge System and the Distances from the Cities Involved to these Sites

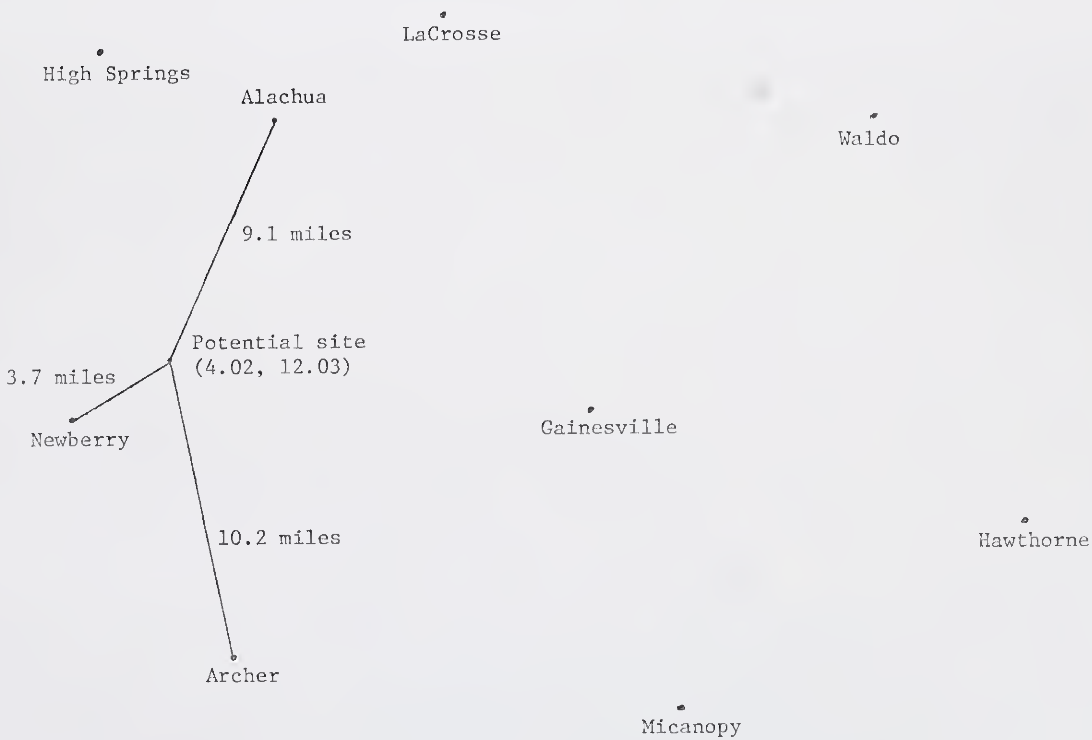


Figure 5.6 Relative Location of Potential Regional Treatment Site for Trickling Filter System and the Distances from the Cities Involved to this Site

Table 5.5 Present Value of Secondary Treatment Costs for the Minimum Cost Option for Alachua County, Florida, 1975 to 1990[a]

City	Activated Sludge System		High-rate Trickling Filter System	
	1975	1990	1975	1990
High Springs	---	39,059 (.0871)	969,928 (.4455)	33,919 (.0871)
Newberry	---	23,559 (.0385)	583,362 (.2011)	20,183 (.0385)
Archer	---	21,182 (.0324)	483,274 (.1498)	18,094 (.0324)
Alachua	---	48,008 (.1215)	1,016,294 (.4792)	41,920 (.1215)
Gainesville Urban Area	6,204,332 (6.5446)	697,737 (9.0876)	5,410,354 (6.5446)	652,094 (9.0876)
LaCrosse	366,428 (.0655)	13,438 (.0155)	284,666 (.0655)	11,337 (.0155)
Micanopy	520,765 (.1161)	6,441 (.0047)	410,530 (.1161)	5,324 (.0074)
Waldo	533,672 (.1208	12,325 (.0135)	421,134 (.1208)	10,373 (.0135)
Hawthorne	675,850 (.1775)	16,799 (.0223)	538,577 (.1775)	14,260 (.0223)
R(1, 2, 3, 4)	3,588,569[b] (1.2756)	---	---	---

[a]All costs are in September 1974 dollars.

[b]This figure includes pumping and transmission costs.

Table 5.6 Present Value of Secondary and Tertiary Treatment Costs for the Minimum Cost Option for Alachua County, Florida, 1975 to 1990[a]

City	Activated Sludge System		High-rate Trickling Filter System	
	1975	1990	1975	1990
High Springs	---	73,790 (.0871)	2,248,431 (.4455)	68,651 (.0871)
Newberry	---	42,890 (.0385)	---	39,514 (.0385)
Archer	---	38,313 (.0324)	---	35,225 (.0324)
Alachua	---	92,373 (.1215)	---	86,285 (.1215)
Gainesville Urban Area	31,090,496 (16.0446)	1,535,004 (4.5876)	30,296,512 (16.0446)	1,489,361 (4.5876)
LaCrosse	673,327 (.0655)	23,738 (.0155)	591,564 (.0655)	21,637 (.0155)
Micanopy	986,469 (.1161)	11,089 (.0047)	876,234 (.1161)	9,972 (.0047)
Waldo	---	21,690 (0.35)	900,693 (.1208)	19,739 (.0135)
Hawthorne	---	29,997 (.0223)	1,176,076 (.1775)	27,458 (.0223)
R(8, 9)	2,297,853[b] (.2983)	---	---	---
R(2, 3, 4)	---	---	4,474,878[b] (.8301)	---
R(1, 2, 3, 4)	6,506,944[b] (1.2756)	---	---	---

[a]All costs are in September 1974 dollars.

[b]This figure includes pumping and transmission costs.

Table 5.7 Present Value of Wastewater Treatment Costs for Time Option 5 for Alachua County, Florida, 1975 to 1990[a]

City	Activated Sludge System		High-rate Trickling Filter System	
	tertiary processes		tertiary processes	
	with	without	with	without
High Springs	---	---	2,554,474 (.5326)	1,087,224 (.5326)
Newberry	---	---	---	652,435 (.2396)
Archer	---	---	---	547,699 (.1822)
Alachua	---	---	---	1,174,284 (.6007)
Gainesville Urban Area	41,808,368 (20.6322)	10,602,925 (15.6322)	40,650,256 (20.6322)	9,444,815 (15.6322)
LaCrosse	775,558 (.0810)	417,534 (.0810)	684,164 (.0810)	326,139 (.0810)
Micanopy	1,013,231 (.1208)	533,672 (.1208)	900,693 (.1208)	421,134 (.1208)
Waldo	---	569,520 (.1343)	969,109 (.1343)	450,637 (.1343)
Hawthorne	---	726,721 (.1998)	1,277,120 (.1998)	580,857 (.1998)
R(8, 9)	2,478,977[b] (.3341)	---	---	---
R(2, 3, 4)	---	---	5,185,699[b] (1.0225)	---
R(1, 2, 3, 4)	7,474,954[b] (1.5551)	4,052,585[b] (1.5551)	---	---

[a]All costs are in September 1974 dollars.

[b]This figure includes pumping and transmission costs.

are different. Again the figures in parentheses under each set of cost figures are the capacities to be built.

North Central Florida Regional Planning Council [1973] has six alternatives toward supplying wastewater treatment facilities in Alachua County and these alternatives are shown in Table 5.8. There are differences between their estimated capacities and those used in this study. There are also differences in basic assumptions used in consolidations over space and time, e.g., highway milages were used in NCFRPC's study instead of a Euclidean distance measurement which was used in this study. Therefore, a meaningful comparison between their alternatives and the results of this study is difficult.

Table 5.8 Alternative Plans of Regional Wastewater Utilities in Alachua County as Suggested by NCFRPC

Alternative	Regional Plants
I	$\sum_{i=1}^{9} R(i)$
II	R(5, 7, 8, 9) + R(1, 2, 3, 4, 6)
III	R(1, 2, 3, 4, 6) + R(8, 9) + R(5) + R(7)
IV	$R(1, 4, 6) + R(2, 3) + R(5) + \sum_{i=7}^{9} R(i)$
V	$R(1, 2, 4) + R(3) + \sum_{i=5}^{9} R(i)$
VI	$R(1, 4, 5,^{a} 6) + R(2) + R(3) + R(5^{b}) + \sum_{i=7}^{9} R(i)$

[a]This regional treatment plant serves only part of the NW section of Gainesville.

[b]This regional treatment plant serves Gainesville except for the part of NW Gainesville.

Source: North Central Florida Planning Council [1973].

CHAPTER VI
LANDSPREADING SECONDARY EFFLUENT AS A SUBSTITUTE FOR TERTIARY TREATMENT PROCESSES

The technology employed in wastewater treatment has not advanced much in the past several decades. There are several difficulties one encounters when attempting to remove more than 95% of the BOD and SS with the standard processes. Greater removals require very large increases in detention times and a corresponding increase in tank sizes. A second treatment problem is the removal of nutrients. Nitrogen and phosphorous compounds are more likely to be responsible for excess weed growth than BOD. Standard processes do not do a good job of removing these nutrients. These two problems can be handled by tertiary treatment processes; however, the cost for these treatment processes alone is higher than the cost of conventional treatment processes. Land treatment is therefore considered as an alternative to tertiary waste treatment.

Briefly stated, land treatment involves the use of agricultural land and crops or forest products to absorb and filter nitrates, phosphates, and other elements from wastewater that has undergone primary and, usually, secondary treatment. Excess "purified" water is then returned to the water course. The methods of applying wastewater to the land can be identified as infiltration systems, crop irrigation systems, and spray-runoff systems [Thomas, 1973; Thomas and Law, 1968]. Infiltration systems are usually designed to prevent surface runoff. High loading rates make evaporative losses relatively insignificant.

and up to 99% of the applied wastewater may be contributed to ground water as recharged [Laverty et al., 1961]. Crop irrigation systems may or may not control surface runoff. Low loading rates allow much of the applied wastewater to be lost through evapotranspiration, and the contribution to ground water is largely dependent on evapotranspiration losses [Dalton and Murphy, 1973; Graveland and Vickerman, 1972; Parizek et al., 1967; Sprout and Hopkins, 1972; Young et al., 1972]. Spray runoff systems are designed to return 50% or more of the applied wastewater as direct surface runoff, evapotranspiration losses are variable but relevant, and the selection of sites with impermeable soils restricts the contribution to ground water [Law et al., 1970]. The application of wastewater to land serves the following purposes: promotes growth of crops, conserves water and nutrients that are normally wasted, provides economical treatment of the wastewater, and reduces the pollution load on surface water supplies.

Many researchers have contributed estimates of the fertilizer value in treated sewage effluent, and the values vary with the study, with the type of treatment given to the sewage effluent, and with the source of effluent. Schreiber [1957] reports that the amount of the principal fertilizer elements in sewage effluents from 15 California cities studied is 60 to 100 pounds of nitrogen chiefly in the form of ammonia; 20 to 40 pounds of potassium occuring as potassium; and 60 to 100 pounds of phosphate occuring as phosphate, per acre-foot of effluent. Schreiber does not assign a dollar value to the fertilizer contained in an acre-foot of effluent; however, Hirsch [1959] states that the 1969 value of nitrogen, phosphorus and potassium fertilizer in an acre-foot of typical San Diego wastewater is $18. A Pennsylvania State University research experiment [Parizek _et al._, 1967] attempted to relate effluent-derived agricultural nutrients to an equivalent commercial fertilization rate. In this case the investigators determined that with an application rate of two inches of effluent per week for periods varying from 24 to 33 weeks of irrigation in three years of study (1963-1965), fertilizer application to crops and wooded plots was equal to 100 to 280 pounds of nitrogen, 180 to 300 pounds of available phosphorus, and 120 to 320 pounds of water soluable potash per acre.

From research on the effect of sewage farming on crop yields, it is evident that most crops produce much higher yields when irrigated with effluent than when not irrigated or when irrigated with ordinary water but not commercially fertilized [Parizek _et al._, 1967; Day and Tucker, 1959].

The suitability of domestic wastewater for irrigation depends on the chemical composition of water supplies and how this composition is affected by the use cycle. For instance, salinity and the ratio of sodium to calcium and magnesium are important factors in judging suitability of water from saline soil solutions, the osmotic pressure of such solutions interferes with the movement of water from the solution into the plant root, and the plants may suffer from incipient drought. Sodium soils are relatively impermeable to air and water; they are hard when dry, difficult to till, and plastic and sticky when wet. These adverse physical conditions retard or prevent germination and water removal by plants and are generally unfavorable for plant growth.

Most of the public reservations concerning the use of treated sewage effluent for irrigation and fertilization stem from the feeling that the effluent is unclean, unaesthetic, and contaminated with disease organisms. Because of this attitude, the current general practice in the United States is to provide at least primary treatment and to utilize treated sewage for irrigation of nonfood crops only. Secondary treatment and chlorination greatly improved the quality of sewage, and for aesthetic safety reasons these conventional wastewater treatment processes are recommended for upgrading municipal wastewater before irrigation use.

Possibly the most significant standard for irrigation water, from the standpoint of public interest, is that for bacterial count. Restrictions on coliform counts, the primary index used for bacterial contamination, are relatively rigorous for irrigation water. But it is important to realize that the presence of coliform bacteria in wastewater is only an indication of the potential presence of pathogenicity, as coliform bacteria themselves are not pathogenic.

Another most pressing, most difficult and expensive unknown to be determined is the fate of viruses present in effluent used for spray irrigation. Even the most efficient secondary treatment plants fail to produce virus-free effluents [Kollins, 1966]. The field studies at Stanford University, Hawaii, and MIT [Drewry, 1973] have negative results on the tests for virus existance in the test wells. However, Wellings et al. [1974] report that they have isolated virus from the effluent used for spray irrigation from the spray just before it enters the soil, and from weir water which represents effluents percolated through 20 feed of sandy soil at St. Petersburg Northwest Wastewater Treatment Plant, Florida.

Farmers ordinarily irrigate the best soils or fields on their farms. The same should be true for municipalities when irrigating with effluent. Unfortunately, too many make the sad choice of acquiring the cheapest land available which often is too wet, too steep, or has insufficient soil depth to provide adequate renovation.

New concepts are required when managing irrigation systems for wastewater disposal. Whereas farmers ordinarily irrigate for crop requirements, in wastewater irrigation the need is to manage for adequate water renovation. The crop is secondary. This suggests that usually the municipality or company producing the wastewater should own the land and not the farmer. A farmer whose income is from the sale of crops will find it difficult to irrigate a crop which perhaps already has more water than it needs. In wastewater disposal management, one normally applies maximum amounts of water to land, not optimal amounts for crops. Most of the irrigation research and experience to date has been oriented toward crop objectives and not wastewater disposal.

Monitoring of the effluent which leaves the renovation area is an essential part of system management. Both surface and subsurface water discharge should be monitored in each dominate direction of water egress. Monitoring facilities usually assay only the quality of the discharge from the renovation area. Under proper management, however, quantity also should be considered.

In this study, we assume that secondary treatment and chlorination are required for the effluent to be used in land treatment. According to the results in Chapter V, if only the secondary treatment is required, there is no need to build any regional treatment plant, and each city can satisfy its demands from 1975 to 1990 by the second option mentioned in that chapter. If land treatment is used as a substitute for tertiary treatment and added to the secondary treatment plants, the feasibility of regional land treatment operations comes into question.

The answer to this question will depend on the economies of scale in land treatment and whether the gains in economies of scale are large enough to offset the increase in the costs of transmitting effluent to regional land treatment sites.

Data do not exist to investigate the economies of scale in land treatment operations, nor are there definite studies that can be used for reference. However, there are studies [Wills, 1956; Madden, 1967] on farm size which suggest that economies of size in agricultural production are exhausted by family size farm units, and that cost functions are homogeneous of degree one for modest size units. One would expect a similar situation for land treatment operations.

Meyers [1973] points out that in the design of an irrigation system for any wastewater facility, five variables must be considered. These are daily flow from the facility, weekly loading depth on the land area, hourly application rate, sprinkler spacing, and nozzle operating pressure. These variables are interrelated.

Given these five variables one can attempt to develop an engineering design of the land spreading system. Design parameters to develop such a system have not been developed for Alachua County. And, rather than construct a hypothetical system with data that have little or no relevance for the design problem here in Alachua County, this study presents a cost-minimization model which will determine the desired balance among the multiple objectives of economic crop production, minimum cost waste disposal, and environmental quality objectives.

In general form the model may be presented as a set of eight functions as follows:

$Y = y(E_1, L, X, F)$	crop yield response function	(6.1)
$F = f(E_1)$	nutrient input function	(6.2)
$A = a(E_1)$	land requirement function	(6.3)
$TC_1 = c_1(E_1)$	cost of disposing of E_1 on crop land	(6.4)
$TC_2 = c_2(E_2)$	cost of treating and disposing of E_2	(6.5)
$D_1 = d_1(E_1)$	damage function for E_1	(6.6)
$D_2 = d_2(E_2)$	damage function for E_2	(6.7)
$C_L = c_L(L)$	cost function for land	(6.8)

where:

E_1 = quantity of secondary effluent to be applies to land in crops

E_2 = quantity of secondary effluent for disposal by an alternative method, say, tertiary treatment

E = total quantity of secondary effluent for disposal

F = total quantity of nutrients in E_1

TC_1 = cost of transporting and applying waste, E_1 to cropland

TC_2 = cost of treating and disposing of secondary effluent, E_2, by tertiary treatment

L = acres of cropland used for waste disposal

X = quantity of resources (other than E_1 and L) used in crop production

Y = physical quantity of crop production

C_L = cost per acre to gain control of land (maybe rent, annual cost of purchase, etc.)

C_x = cost per unit of non-land and non-waste resources used in crop production

P_y = selling price per unit of crop

D_1 = dollars of damage (considered as a cost to the system) to environmental community caused by use of E_1 on crop land

D_2 = dollars of damage (considered as a cost of the system) to environmental community caused by discharge tertiary effluent of E_2 (alternative to the disposal-on-land method of treatment and disposal)

It is assumed in the model that the decision unit wishes to minimize total cost of disposing of a given amount of secondary effluent E after allowing for damage to the environment and community and any offsetting return from crops. The decision unit may purchase land directly or rent land by the acre on a cash basis or on crop-share basis. Preparation of the land for crop production--e.g., clearing cut-over pine land and establishing pasture may also be included in the cost. Further, the damage to the environment and community by use of both the land-disposal process and the alternative tertiary treatment processes must be borne by the decision unit. Thus, externalities have been internalized.

The objective of the decision unit is to minimize total cost, TC, which is defined as follows:

$$TC = c_2(E_2) + d_2(E_2) + c_1(E_1) + d_1(E_1) - P_y y(E_1, L, X)^1 + c_L(L)L + C_x X \tag{6.9}$$

subject to $E = E_1 + E_2$ or the disposal of all waste generated by the decision unit. Introduce the multiplier and construct the Lagrange function

$$TC + \lambda(E - E_1 - E_2) \tag{6.10}$$

---

[1]Since F is a function of E_1, equation (6.2), therefore $Y(E_1, L, X, F)$ can be rewritten as $Y(E_1, L, X)$.

Taking the first partial derivatives and set them equal to zero, one obtains

$$\frac{\partial TC_1}{\partial E_1} + \frac{\partial D_1}{\partial E_1} - P_y \frac{\partial Y}{\partial E_1} = \lambda \qquad (6.11)$$

$$\frac{\partial TC_2}{\partial E_2} + \frac{\partial D_2}{\partial E_2} = \lambda \qquad (6.12)$$

$$P_y \frac{\partial Y}{\partial L} = C_L + \frac{\partial C_L}{\partial L} L \qquad (6.13)$$

$$P_y \frac{\partial Y}{\partial X} = C_X \qquad (6.14)$$

These four relations, (6.11) through (6.14), together with $E = E_1 + E_2$ provide a solution for the five unknowns, E_1, E_2, L, X, and λ.

The terms on the left of equation (6.11) are the total marginal cost of employing a unit of secondary effluent in land treatment, which include the cost of transporting and applying waste E_1, environmental damage, and return from crops. The term, λ, on the right is the inputed marginal revenue product of the secondary effluent. The equation states the familar proposition that the marginal cost of production must equal inputed marginal revenue product. Equation (6.12) states the same proposition for tertiary treatment of E_2.

Equations (6.11) and (6.12) indicate that the inputed marginal revenue product of secondary effluent must be the same in each of its uses, and the total marginal cost for land disposal method must be equal to the total marginal cost of disposal by tertiary processes.

To show how the rate of effluent application per acre fits into the system, we refer to Figure 6.1(a). With the price of the crop, P_y, fixed, total revenue curve of crop, P_yY, has the same shape as the crop yield response curve. The marginal revenue, $P_y \frac{\partial Y}{\partial E_1}$, indicates the

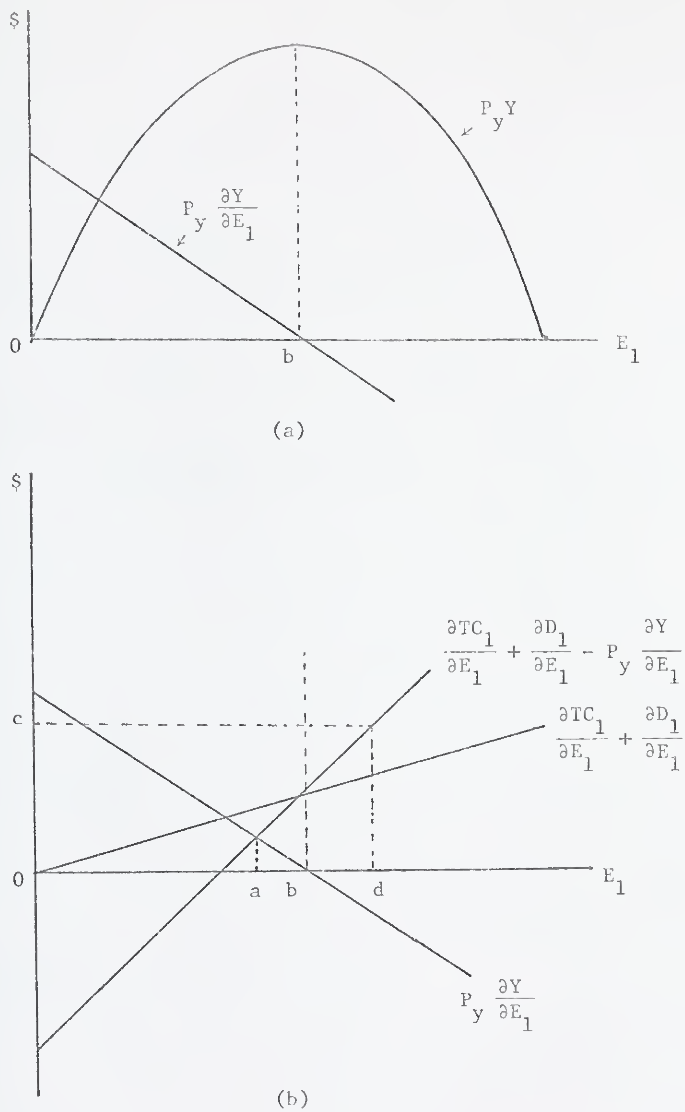


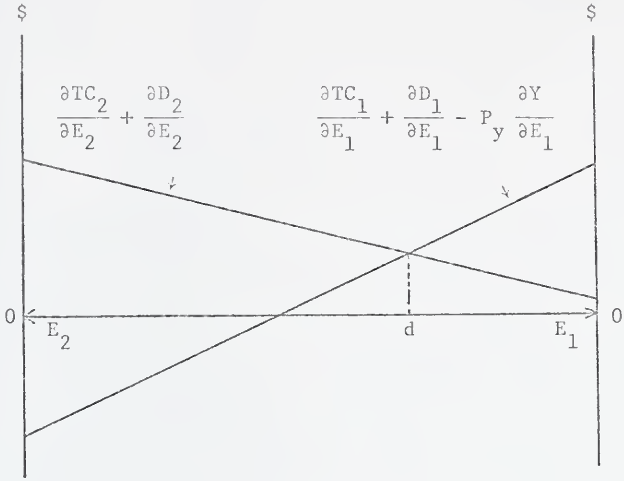
Figure 6.1 Cost Curves of Disposal of Effluent on Land

addition to gross revenue if the effluent, E_1, were costless. Note that if we were to view profitable crop production as the "sole" objective in such a situation, ob is the optimal amount of effluent to apply. If E_1 is not costless, how should it be prices? To answer this, we need to go back to equations (6.11) and (6.12).

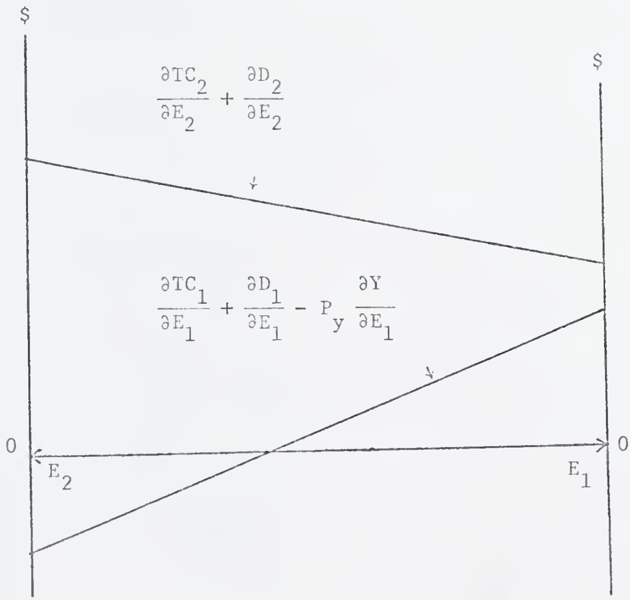
Equations (6.11) and (6.12) are two of the conditions for total cost minimization for the entire system. These conditions indicate that, as mentioned before, the total marginal cost for the land disposal method must be equal to the total marginal cost of disposal by alternative methods. In Figure 6.1(b), the left side of equation (6.11) is depicted. For simplicity, we assume that the functions for yield response (6.1), total cost, TC_1, (6.4), and damage (6.6), are quadratic in E_1, thus giving linear derivatives.

As in Figure 6.1(a), ob represents the amount of effluent, E_1, to be applied for maximum crop yield per acre. Suppose that the total marginal cost for the alternative method, $\frac{\partial TC_2}{\partial E_2} + \frac{\partial D_2}{\partial E_2}$, is oc. This would require an application of effluent in excess of maximum crop yield per acre. If the total marginal cost of the alternative method were to decrease sufficiently, the optimal application rate would drop to less than ob. Optimal application rates less than oa would mean that disposal on land created, in total, an income rather than a cost.

However, this equilibrium may not be reached in some cases. For example, in Figure 6.2, the two vertical lines represent total marginal costs for E_1 and E_2, respectively, and the horizontal line represents the total amounts of secondary effluent disposed of. In panel (a), the equilibrium is reached, and an amount od of effluent will be disposed of by land treatment operation. The rest of E, E-od will be disposed of by



(a) Example for Equilibrium



(b) Example for Disequilibrium

Figure 6.2 Examples of Equilibrium and Disequilibrium Conditions the alternative method. In panel (b), for a given amount of E, there is no intersection for these two marginal cost curves. There is no equilibrium involving both methods, and land treatment provides the least cost method of disposing of all the effluent. Of course, the reverse situation may also occur if the marginal cost of the land treatment operation is dominated by the marginal cost of the alternative method.

Equations (6.13) and (6.14) state that, under equilibrium conditions, the value of marginal product of a factor equals the marginal cost of this factor. As indicated by equation (6.8), the price of land may be a function of the amount of land required for land treatment operations. The right side terms of equation (6.13) show that the marginal cost of land acquisition is a function of the amount of land acquired, and equation (6.14) shows the marginal cost for other inputs to be a constant, C_x.

Of course, other variables besides the marginal cost of alternative disposal methods could affect the optimal application rate; for example, the other two conditions shown by equations (6.13) and (6.14). The marginal value product of effluent, $\frac{\partial P_y Y}{\partial E_1}$, also has important implication for the price a farmer can afford to pay for varying amounts of effluent, E_1. If crop production is viewed as a separate decision-making unit, the amounts of effluent less than ob have a positive value and could command a price; application in excess of ob would cause financial loss to the crop enterprise and would require compensation.

This model can, of course, be expanded to include more alternative treatments, crop systems, and constraints. However, in any cost minimization model the optimal rate of application of effluent to cropland,

E_1/L, depends on knowledge of the functional relationships (6.1) through (6.8) and prices and costs.

Although in Florida a number of experiments have been conducted to show the effect of irrigating wastewater on pasture and selected crops, very few have made estimates of the yield response to wastewater and fewer experiments have been conducted to develop new management techniques for a land treatment system [Alexander, 1972; Hortenstine, 1973; Institute of Food and Agricultural Sciences, 1973; Overman, 1971; Overman and Smith, 1973]. Such management techniques may include the following: what crop should be grown, what type of irrigation system is best for the desired agricultural enterprise, what is the best irrigation frequency for disposing of wastewater, what is the harvesting requirement for forage crops (grasses) and how often is removal of the forage required. The use of crops and land to renovate wastewater and thus eliminate unwanted materials through so called "living filters" is different from the conventional problems in agricultural production. In a conventional agricultural production problem one tries to maximize net returns subject to limited resources or, on the other hand, to use minimum amounts of resources to produce a certain level of returns. The emphasis has been placed on agricultural production research. While in land treatment systems, the emphasis is placed on the disposal of wastewater and agricultural production plays a secondary role. As a result there is a serious lack of knowledge of management techniques in the areas of negative marginal productivities of resources.

Based upon the input-output relationships developed by the IFAS Irrigation Task Force, Holt [1972] has provided estimates of the production practice necessary to produce crops under irrigation on formerly unfarmed deep sand soils in North and West Florida. A center pivot irrigation system is used to cover a 138-acre area in his study, the initial investment estimate is $200 per acre, and the variable cost estimate is $1.25 per acre per inch of water applied.[2] Table 6.1 shows the estimates for six selected irrigated crops. Column two shows that for six crops, the returns over specified expenses are all negative except sorghum for silage using the 1971 unit prices given in column two. With later prices the crops would be more profitable. Column four shows the cash expenses on fertilizer for the crops.

Overman and Smith [1973] have studied the nutrient composition of secondary effluent at the southwest treatment plant in Tallahassee, Florida. Table 6.2 shows the nutrient composition of secondary effluent in their study and the amounts of nutrient content in the effluent if the irrigation rate is two inches per week for twenty-five weeks. If these nutrients can be used to eliminate the costs of fertilizer, and if there are no adverse effects, then it would be profitable for all the six crops mentioned in Table 6.1 except soybeans for beans (see Column 5). Further, if calcium is obtained from secondary effluent, all the six crops would be profitable. However, the possibility of having adverse effects by the application of excess water and nutrients were not considered by Overman.

Table 6.3 shows the estimated total expenses per acre of the irrigated crops mentioned above by Holt [1972]. Table 6.4 shows the land preparation and irrigation system costs from three studies. Based on a

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[2] Based on an irrigation frequency of 5 days, 6 inches annually, and total initial investment includes deep well, pump, power unit and system, but no depreciation.

Table 6.1 Estimated Returns and Fertilizer Costs per Acre of Selected Irrigated Crops on the Deep Sands of North and West Florida

Operation	Return over Specified Expenses (dollars)[a]	Unit Price of Output[b]	Cash Expenses for Fertilizer (dollars)[c]	Net Return (dollars)
Corn for Grain	-29.89	$ 1.10/bu.	39.20	9.31
Corn for Silage	-5.12	$ 8.00/ton	41.70	36.58
Sorghums for Grain	-33.76	$ .90/bu.	34.70	0.94
Sorghums for Silage	9.93	$ 7.50/ton	41.70	43.63
Soybeans for Beans	-11.02	$ 2.20/bu.	8.70	-2.32
Coastal Bermudagrass for Hay	-7.15	$30.00/ton	52.70	45.55

[a]Expenses do not include unallocated overhead costs such as insurance or depreciation charges on farm buildings, tractors and equipment, farm taxes, or pickup expenses.

[b]Prices are those experienced in 1971.

[c]These figures do not include the cash expenses on lime, which is $3.33 per acre at an application rate of .33 ton per acre. And these figures include the expenses on N, P_2O_5, K_2P, and FTE 504 except for soybeans for beans, in which there is no expense on nitrogen.

Source: Holt [1972].

Table 6.2 Nutrient Composition of Secondary Effluent at Southwest Treatment Plant in Tallahassee

Element	lb./acre-in[a]	Irrigation Rate (2 in/wk.)[b] (lb./acre)
N	8.2	410
P	2.7	135
K	1.4	70
Ca	7.1	355
Mg	2.2	110
Na	8.9	445
Cu	less than 0.02	---
Fe	0.11	5.5
Zn	0.033	1.6

[a] From composite samples for period April 5, 1972 to September 27, 1972.

[b] Based on twenty-five weeks of irrigation.

Source: Overman and Smith [1973].

Table 6.3 Estimated Total Expenses per Acre of Selected Irrigated Crops on the Deep Sands of North and West Florida

Operation	Cash Expenses				Land Rent	Total Expenses
	Total (1)	Fertilizer (2)	Lime (3)	(1)-(2)-(3)		
Corn for Grain	103.73	39.20	3.33	61.20	17.00	78.20
Corn for Silage	128.00	41.70	3.33	82.97	17.00	99.97
Sorghum for Grain	88.23	34.70	3.33	50.20	17.00	67.20
Sorghum for Silage	121.23	41.70	3.33	76.20	17.00	93.20
Soybeans for Beand	64.44	8.70	3.33	52.41	17.00	69.41
Coastal Bermudagrass for Hay	178.02	52.70	3.33	122.00	17.00	139.00

Source: Holt [1972].

Table 6.4 Estimated Costs of Land Preparation and Irrigation System

Item	Cost Estimates		
	Muraro	Anderson and Hipp	Holt
I. Land Preparation (per acre)			
pongola pasture	$100.70	---	---
burmudagrass and clover or pongola and clover pasture	---	$109.67	---
straight burmudagrass or pongola pasture	---	$101.91	---
bahai and clover pasture	---	$ 93.26	---
straight bahai pasture	---	$ 89.52	---
argentina-bahai pasture	---	$ 98.26	---
II. Irrigation System			
permanent overhead[a]			
construction	$596.64/acre	---	---
O&M	$133.48/acre/year	---	---
self-propelled volume gun[a]			
construction	$490.40/acre	---	---
O&M	$211.95/acre/year	---	---
central pivot			
construction	---	---	$200.00/acre
O&M	---	---	$ 1.25/acre-inch

[a]These are estimates calculated from an effluent flow at 5 mgd, and application rate at approximately 2.05 inches per acre per week.

640-acre irrigation site, Muraro [1972] has estimated the costs for a land-spreading system. Anderson and Hipp [1973] have estimated the costs of land preparation for selected pastures. And Holt [1972], as mentioned before has estimates for central pivot irrigation system.

For a 140-acre field, Westberry [1974] has estimated the costs of owning and operating a central pivot irrigation system, and the cost of corn production with and without irrigation. According to his estimation, the cost per bushel of corn is $1.70 with irrigation, and $1.75 without irrigation with estimated productions of 155 bushels per acre and 60 bushels per acre, respectively. His results show that a corn grower receives a higher expected revenue with an irrigation system.

The results from Holt [1972] and Westberry [1974] show that irrigation has the potential not only to increase yield but to provide insurance against the possibility of serious yield reduction due to prolonged dry periods.

The most important unknown is whether an agricultural land treatment system will adequately purify water to meet acceptable standards. If so, the cost of such treatment is considerably below that for tertiary treatment. If one assumes that on site a land treatment operation can break-even, one can estimate how far secondary effluent can be pumped to a land treatment site and still compete with tertiary treatment.

Westberry [1974] has estimated the fixed cost of a center pivot irrigation system as $51.07 per acre annually, and a variable cost of $2.06 per acre inch of water applied. A center pivot system operates in a 160-acre block and irrigates a circular area of 138 acres.

Baldwin [1975] has estimated a fixed cost of $96 per acre annually and a variable cost of $1.65 per acre inch of water applied for such a system.[3]

Table 6.5 shows pipeline and pumping station costs for time options 2 and 5 (Table 5.1) and the estimated irrigation system cost from Westberry [1974] and Baldwin [1975].

From these cost figures, one finds that time option 2 provides a minimum cost of pipeline per mile for the cities of High Springs, Newberry, Archer, Alachua, and the Gainesville Urban Area, and time option 5 provides a minimum cost for LaCrosse, Micanopy, Waldo, and Hawthorne. The different time option for the latter four cities is probably due to their small population changes between 1975 and 1990.

Wastewater estimates for all cities in Alachua County except those for the Gainesville Urban Area were small. Therefore, time option 5 was used to calculate irrigation system costs for all communities except for the Gainesville Urban Area. If other time options had been used, some flows would have been too small to be realistic for the construction of an irrigation system. Time option 2 was used for the Gainesville Urban Area. All systems costs include construction and operation and maintenance costs.

The difference between the cost of tertiary treatment and site costs for land spreading were used to estimate break-even distances over which effluent could be moved for land spreading purposes (Table 6.6). Baldwin's [1975] cost estimates (column 6 in Table 6.5) and a high-rate trickling filter system were used for the calculation. Break-even

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[3] These cost figures were derived from Harrison's [1975] work.

Table 6.5 Present Value of Cost of Transmission Pipeline per Mile, Pumping Station, and Irrigation Systems for Alachua County, Florida, 1975 to 1990[a]

City	Pipeline per Mile		Pumping Station		Irrigation Systems	
	Option 2[b]	Option 5[b]	Option 2[b]	Option 5[b]	Westberry	Baldwin
High Springs	27,877	28,482	315,585	350,995	48,417	86,525
Newberry	18,917	19,066	174,045	193,161	21,796	38,939
Archer	16,605	16,735	140,007	157,414	16,535	29,582
Alachua	29,180	30,343	335,233	384,084	59,487	106,883
Gainesville Urban Area	219,401	237,686	2,572,519	4,400,404	630,597	1,125,887
LaCrosse	11,795	11,751	75,543	85,852	7,337	13,139
Micanopy	14,414	13,919	113,312	115,766	11,135	19,750
Waldo	14,833	14,584	117,850	125,306	12,305	21,898
Hawthorne	17,681	17,488	157,389	168,615	18,286	32,558

[a] All costs are in September 1974 dollars.

[b] See Table 5.1 for a definition of time option.

distances show how far one could transport the secondary effluent from each source for land spreading and be indifferent between land spreading and tertiary treatment.

Table 6.6 shows the break-even distances for time options 2 and 5. These results show that secondary effluent can be transported considerable distances for land treatment and still compete with tertiary processes.

In estimating break-even distances, it was assumed that Newberry, Archer, and Alachua shared regional tertiary treatment costs in proportion to their wastewater flows. The shares of their wastewater flow are 0.2423, 0.1805, and 0.5773, and their corresponding assessment in 1975 was assumed to be \$579,569, \$432,747, and \$1,380,872 respectively.

If these estimates are correct, and if soil and crops could eliminate nutrients and unwanted materials from secondary effluent effectively, then the cost for land treatment would be the difference between the site preparation, transmission and pumping costs, and the net return from crop productions, which is considerably less expensive than tertiary treatment.

Relationships (6.2), (6.4), and (6.5) involve basically engineering estimates and it would be expected that the parameters in these equations could be estimated with relatively greater precision than (6.1) which is an essentially biological relationship. If (6.5) refers to a tertiary system of treatment and disposal, one would expect that the estimates in previous chapters, together with the updating of costs, would give rather precise knowledge of this relationship.

Knowledge is most meager in the case of damage functions, (6.6) and (6.7). Although these damages are expressed in dollars, in the case of

Table 6.6 Break-even Length of Transmission Pipeline for Land Treatment in Alachua County, Florida, 1975 to 1990

City	Tertiary Process Cost		Break-even Distance (miles)[b]	
	Option 2	Option 5	Option 2	Option 5
High Springs	1,313,235	1,467,250	32.68	36.94
Newberry	598,880	658,683	20.40	22.55
Archer	448,878	500,970	16.82	18.91
Alachua	1,425,237	1,651,628	33.69	39.78
Gainesville Urban Area	25,723,425	31,205,441	100.39	117.04
LaCrosse	317,198	358,025	19.45	22.04
Micanopy	470,352	479,559	24.23	24.72
Waldo	488,925	518,472	23.94	25.46
Hawthorne	650,697	696,263	26.35	28.31

[a]Calculated from Tables 5.5, 5.6, and 5.7.

[b]Calculated from Table 6.5. These figures were obtained by subtracting costs of pumping station and Baldwin's irrigation system cost from tertiary process cost then divided by the cost of pipeline per mile.

many of the potentially harmful aspects of applications of wastewater the fundamental physical relationships are not known. Damages may also be difficult to measure in dollars. For example, the life of a person is difficult to express in dollars, and the transformation in space and time of heavy metals represents processes that are not well understood. It is for such reasons that policy normally attempts to reduce potential adverse environmental impacts by setting rather subjective standards.

Functions (6.6) and (6.7) may not be linear, since these damages depend not only on the amount of effluent disposed but also on the rate of application. For example, if tertiary treatment is used, the damages shown by (6.6) are functions of the amount of effluent disposed as well as the effluent disposal rate. The ability of the environment to restore itself is limited and more or less constant over a given period of time. If a regional treatment plant treats wastewater for the whole county and releases its tertiary effluent at one location, the rate of pollutants released at this location is still tremendous even though the pollutant contents of the effluent are low, and hence create an environmental hot spot. The same result may happen if land treatment is used. This damage to the environment may discourage the regionalization of wastewater treatment facilities.

The management and operation of wastewater treatment facilities add to county incomes both directly and indirectly. The proportions of these expenses that go into the county's business and household sector, respectively, determines the final effects of treatment on county income. The indirect effects of treatment on county income are important and should not be ignored. Since agricultural production normally creates considerable indirect activity one would expect that the land treatment alternative would have greater beneficial impact on the community than would tertiary treatment.

The state of the arts in advanced wastewater treatment is still in its developmental stage. There remains considerable uncertainty as to the effectiveness of both chemical and land spreading methods for advanced treatment. The effectiveness of land spreading seems to be site specific and a function of such factors as type of soil and slope of land. The effectiveness of tertiary processes in a real world treatment situation also remains in question.

CHAPTER VII
SUMMARY AND DISCUSSION

Summary

In the planning and design of a wastewater treatment facility for a city, town, or an area where the requirements for treatment are expected to increase with time, the initial size of the treatment plant and the timing of capacity additions and/or replacements over some time horizon need to be answered in the context of an optimal staging policy.

The economies of scale provide the main incentive for regionalization for wastewater treatment facilities as well as for constructing larger initial treatment plant sizes and the timing of capacity additions and/or replacements over some time horizon. Several studies have been made that have discovered the existence of economies of scale in both the construction and operation and maintenance costs of wastewater treatment.

These economies of scale come mainly from the following sources. In the process industries, such as petroleum refining and chemical production, the output of a processing unit tends within certain physical limits to be roughly proportional to the volume of the unit, other things being equal. The amount of materials and fabrication effort required to construct the unit is more apt to be proportional to the surface area of the unit's reaction chambers, storage tanks, connecting pipes, etc. Since the area of a sphere or cylinder varies as the two-thirds power (or six-tenths) of volume, the cost of constructing process industry plants can be expected to rise as the two-thirds power of their output capacity. By the same token, there are economies of scale in operation and maintenance costs. In addition, a host of other advantages such as more qualified operating personnel, and higher degrees of automation may be gained through the utilization of this concept.

It is quite clear that economies of scale do exist in wastewater treatment. However, there are several reasons why unit costs do not decline indefinitely. These reasons include the difficulty of managing and operating an enterprise of an increasingly large scale volume of production, and the increases in the transportation costs of raw sewage for large scale treatment plants. In this study, the emphasis has been placed on the trade-offs between the gains in economies of scale in treatment and the increase in transportation costs of raw sewage over space, and the trade-offs between the gains of economies of scale in treatment and the increase in construction costs over time.

Alachua County, Florida was chosen as the study area. Population estimates of years 1975, 1980, and 1990 for each of the nine incorporated cities in the county were obtained from the estimates provided by the North Central Florida Regional Planning Council [1973]. The required treatment capacities for 1975, 1980, and 1990 for the nine cities were estimated by multiplying population projections by 135 gallons per capita per day--an average sewage flow provided by Loehr [1968].

Two types of secondary treatment and three tertiary treatment processes were considered throughout the study: high-rate trickling filter system, activated sludge system, and two clarifier lime clarification processes, lime recalcination, and ammonia stripping process, respectively. The relationships between capacity and construction and operation and maintenance costs were obtained from EPA studies [EPA, 1973a; Michel and Johnson, 1970; Smith and McMichael, 1969; Smith and Eilers, 1971].

The concept of regionalization has two aspects: one is the number of separate sewerage systems operated by a single authority, i.e., the centralization of administration; and the other is a single connected sewer system serving several municipalities with one central plant.

An optimization model for the search of minimum cost combination of regional wastewater treatment plan over space and time was developed. This model provided a guideline for the development of a heuristic method of developing an optimal staging process for wastewater treatment in Alachua County.

The space and time dimensions of regionalization were considered. In order to find the potential sites of regional treatment plants, a cost minimization model was used. For the consolidation over time an exponential objective function was minimized subject to some discrete capacity requirements.

The rates of increase in cost over time were estimated from EPA cost indexes as .12, .10, and .07 per year for force main construction cost, pumping stations and sewage treatment plant construction costs, and O&M costs for both force main and sewage treatment plant, respectively. Service lives for pumping station and wastewater treatment plants were taken as 25 years, and for pipelines as 50 years. An interest rate of 5% per year was assumed.

A least cost staging policy to satisfy the wastewater treatment requirements of the nine cities in Alachua County, Florida for the years 1975, 1980, and 1990 was determined with the model. The results were sensitive to the required quality of secondary effluents.

If the required quality of secondary effluent is set at above 80% removal, activated sludge plants were required to provide the least cost method of treating wastewater. The results show that secondary treatment cost will be minimized if High Springs, Alachua, Archer, and Newberry cooperate to build a regional treatment plant in 1975 to satisfy their 1980 demands, and then construct individual plants in 1990 to satisfy the additional demands at that time. The other cities could satisfy their demands by building individual activated sludge plants in 1975 to satisfy their 1980 demands, with additions being made in 1990. The minimum tertiary treatment cost combination would require the construction of two regional treatment plants, one for High Springs, Alachua, Archer, and Newberry, and one for Waldo and Hawthorne in 1975 to satisfy the 1980 demands of these six cities. Their additional demands in 1990 would be met with plants in each city. Gainesville, LaCrosse, and Micanopy would satisfy their tertiary treatment demands with individual plants constructed in 1975, with additions in 1990.

If the required quality of secondary effluent is set at 80% removal, the results show that secondary treatment cost for the county will be minimized if each city builds a trickling filter plant which satisfy 1980's wastewater treatment demands in 1975, with additions to capacity being made in 1990. The minimum tertiary treatment cost combination suggests that there will be regionalization of treatment in 1975 to satisfy the 1980 demands of three cities--Newberry, Archer, and Alachua. Additional demands in 1990 will be satisfied by building individual treatment plants in these three cities. The other six cities would satisfy their tertiary treatment with individual plants constructed on the same schedule as the trickling filter plants.

One of the objectives of this study has been the study of the trade-offs between the construction of tertiary treatment processes and the usage of secondary effluent as irrigation water. Under conventional secondary treatment about 90% of BOD is removed. Almost no nitrogen and phosphorous are removed. Thus, secondary effluent may cause problems of overgrowth of vegetation in receiving waters. Cost of removing wastes above 95% increase rapidly. Land treatment by irrigation, through the uptake of nutrients by crops or grass may attain a higher removal of BOD and COD and remove up to 98% of the nutrients in secondary effluent. However, precise knowledge of the land treatment process is not available.

The possibilities of substituting land for tertiary treatment was discussed, and the factors which should be considered in land treatment were discussed with the aid of an optimization model. The break-even distances of transmission pipelines for land treatment as a substitute for tertiary treatment were calculated and presented for the nine cities in Alachua County, Florida.

Discussion

Factors such as arrangement of outfall structure, cost allocation among participants, methods of financing, and methods of implementation have not been considered in this study.

The main purpose of this study was to consider the time and space dimension of regional wastewater treatment planning. Because of distances between cities, the gains in economies of scale in the construction of regional treatment plants to serve more than one city are more than offset by transmission costs of raw sewage from each source to potential treatment sites. Therefore, the minimum cost solution of this study includes two regional treatment plants for activated sludge system, and one regional treatment plant for trickling filter system.

The distance between each two cities were such that only ten combinations of cities were selected by the cost minimization model. In studies where the cities are closer together, the scanning process used by this study may create a larger number of potential sites. If so, the search to find the optimum sites for treatment plants will be more involved and may require the imposition of other constraints.

Requirements for the transmission of wastewater depend on the topographic condition of the area studied. In the design of pipelines and pumping stations, topographic conditions should be taken into consideration. In this study, it was assumed that a pumping station was required for each regional plant; of course, more than one pumping station may be needed in some cases. The process of scanning all the possible sites makes it difficult to take the topographic factor into consideration for each site. However, if a site is excluded from the solution by the assumption of only one pumping station, it would not appear in the solution if more than one pumping station were required. Therefore, the assumption is not critical to the results.

A cost minimization model for a land treatment system was presented. And the break-even distances over which one can transport secondary effluent from sources to land treatment sites as an alternative to tertiary treatment were estimated. An important study topic is the income generated by crop production through the disposal of secondary effluent, and how this income is distributed. This topic has important implications for rural and urban development.

Land, including easement costs, was not estimated in this study. This is a very important variable in the actual implementation of a treatment program--particularly for land treatment.

The impacts of energy crisis on wastewater treatment as well as on land treatment were not discussed. However, one may suspect that the effects of the energy crisis would increase all costs proportionally, and hence, the solution of this study may not be affected.

Another aspect of regionalization, centralization of administration, was not considered for the situation in Alachua County. Since all the cities are not far from each other and their wastewater treatment demands are low, the centralization of management and administration may be feasible to utilize personnel more thoroughly.

APPENDIX I

COMPUTER PROGRAM FOR THIS STUDY

```
      COMMON MM
      COMMON CCR(2,9),WT(3,9),CAP(3,9),CI(2, 3,9),POP(3,9),
     *TRC(3,9),TC(3,9),RTRT(3),RCP(3),RTC(3),RPP(3),RTR(3),
     * TC(3,9),RTRT(3),RCP(3),RTC(3),RPP(3),RTR(3),
     * PMP(3,9),CX(9),CY(9),PP(3,9),WTT(3,9),DIS(9),CP(3,9),
     * CC1(2,3,10),COM1(2,3,10),TCC1(2,3,9),TCOM1(2,3,9),
     * PCOM1(2,3,9),ACAP(3,9),ACP(3,9),RACP(3)   ,AWT(3,10),
     * TAWT(3,9),TRT2(2,3,10),TRT3(2,3,10),FX2(2,3),FX(2,3),
     * TRC2(3,9),PMP2(3,9),RPP2(3),PP2(3,9),FX3(2,3),PCCI(
     * 2,3,9),AWTOM(3,10)
      COMMON WT2(3,9),WTT2(3,9),RTC2(3),TC2(3,9)
      DIMENSION ICU(9)
      READ(5,1) ((CCR(I,J),I=1,2),J=1,9)
      READ(5,2) ((PCP(I,J),I=1,3),J=1,9)
1     FORMAT(2F5.3)
2     FORMAT(3F6.0)
      DO 13 I=1,2
      DO 13 J=1,9
13    CCR(I,J)=CCR(I,J)/2.625
      DO 39 MM=1,4
      DO 10 I=1,3
      DO 10 J=1,9
      ACAP(I,J)=PCP(I,J)*135.0/1000000.
10    CAP(I,J)=PCP(I,J)*135.0/1000000.
      GO TO (72,73,74,74),MM
72    CAP(3,5)=CAP(3,5)-5.0
      CAP(2,5)=CAP(2,5)-9.5
      CAP(1,5)=CAP(1,5)-9.5
      GO TO 77
73    DO 75 J=1,9
      ACAP(3,J)=ACAP(3,J)-ACAP(1,J)
      ACAP(2,J)=ACAP(2,J)-ACAP(1,J)
      CAP(3,J)=CAP(3,J)-CAP(1,J)
75    CAP(2,J)=CAP(2,J)-CAP(1,J)
      CAP(1,5)=CAP(1,5)-5.0-4.5
      CAP(3,5)=CAP(3,5)+4.5
      GO TO 77
74    DO 76 J=1,9
      ACAP(3,J)=ACAP(3,J)-ACAP(2,J)
      ACAP(2,J)=ACAP(2,J)-ACAP(1,J)
      CAP(3,J)=CAP(3,J)-CAP(2,J)
76    CAP(2,J)=CAP(2,J)-CAP(1,J)
      CAP(1,5)=CAP(1,5)-5.0-4.5
      CAP(3,5)=CAP(3,5)+4.5
      GO TO 77
77    DO 11 I=1,3
      DO 11 J=1,9
      TRC2(I,J)=CAP(I,J)*3.5
      PMP2(I,J)=P[illegible]G(TRC2(I,J),I,J,1)
      WT2(I,J)=TR[illegible](TRC2(I,J),I,J,1)
      TRC(I,J)=CAP(I,J)*3.5
```

```
      PMP(I,J)=PMG(TRC(I,J),I,J,2)
11    WT(I,J)=TRM(TRC(I,J),I,J,2)
      DO 12 K=1,2
      DO 12 I=1,3
      DO 12 J=1,9
12    CALL TRT(K,I,CAP(I,J),ACAP(I,J),J)
      WRITE(6,3)
3     FORMAT('1')
      WRITE(6,4) ((POP(I,J),J=1,9),I=1,3)
4     FORMAT(' ',///' POPULATION'/' ',3(/' ',9F14.0))
      WRITE(6,41) ((COR(I,J),J=1,9),I=1,2)
41    FORMAT(' '///' CORDINATE IN MILES',/' ',2(/' ',9F14.4)
     * )
      WRITE(6,42) ((CAP(I,J),J=1,9),I=1,3)
42    FORMAT(' '///' TRT CAPACITY IN MGD'/' ',3(9F14.4,/' ')
     * )
      WRITE(6,83)((ACAP(I,J),J=1,9),I=1,3)
83    FORMAT(' '///' AWT  CAPACITY ',3(/' ',9F14.4))
      WRITE(6,81) (((TRT2(K,I,J),J=1,9),I=1,3),K=1,2)
81    FORMAT(' '///' INDIVIDUAL TRT2 COST',6(/' ',9F14.2))
142   WRITE(6,46)((CC1(K,I,J),J=1,9),I=1,3)
46    FORMAT(' '///' PRESENT TRT CONST COST'/' ',3(/' ',9F14
     * 2))
      WRITE(6,48)((COM1(K,I,J),J=1,9),I=1,3)
48    FORMAT(' '///' PRESENT TRT O+M COST',3(/' ',9F14.2))
      WRITE(6,82) (((TRT3(K,I,J),J=1,9),I=1,3),K=1,2)
82    FORMAT(' '///' INDIVIDUAL TRT3 COST',6(/' ',9F14.2))
       WRITE(6,85)((PMP2(I,J),J=1,9),I=1,3)
85    FORMAT(' '///' CONVENTIONAL PMP COST',3(/' ',9F14.2))
      WRITE(6,49)((TCC1(1,I,J),J=1,9),I=1,3)
49    FORMAT(' '///' PRESENT TRM CONST COST',3(/' ',9F14.2))
      WRITE(6,50)((TCOM1(1,I,J),J=1,9),I=1,3)
50    FORMAT(' '///' PRESENT TRM O+M COST',3(/' ',9F14.2))
      WRITE(6,44) ((WT(I,J),J=1,9),I=1,3)
44    FORMAT(' '///' TRANSMISSION COST',3(/' ',9F14.2))
      WRITE(6,22)((TCC1(2,I,J),J=1,9),I=1,3)
22    FORMAT(' '///' TRT3TRM CONST COST',3(/' ',9F14.0))
      WRITE(6,23)((TCOM1(2,I,J),J=1,9),I=1,3)
23    FORMAT(' '///' TRT3TRM O+M COST',3(/' ',9F14.0))
      WRITE(6,26)((PMP2(I,J),J=1,9),I=1,3)
26    FORMAT(' '///' TRT2 PMG COST',3(/' ',9F14.0))
      WRITE(6,51)((PCC1(1,I,J),J=1,9),I=1,3)
51    FORMAT(' '///' PRESENT PMP CONST COST',3(/' ',9F14.2))
      WRITE(6,52)((PCOM1(1,I,J),J=1,9),I=1,3)
52    FORMAT(' '///' PRESENT PMP O+M COST',3(/' ',9F14.2))
      WRITE(6,45) ((PMP(I,J),J=1,9),I=1,3)
45    FORMAT(' '///' PUMPING COST ',3(/' ',9F14.2))
      WRITE(6,24)((PCC1(2,I,J),J=1,9),I=1,3)
24    FORMAT(' '///' TRT3 PMP CONST COST',3(/' ',9F14.0))
      WRITE(6,25)((PCOM1(2,I,J),J=1,9),I=1,3)
25    FORMAT(' '///' TRT3 PMP  O+M  COST',3(/' ',9F14.0))
```

```
      WRITE(6,53) ((AWT(I,J),J=1,9),I=1,3)
53    FORMAT(' '///' PRESENT AWT CONST COST',3(/' ',9F14.2))
      WRITE(6,54) ((AWTOM(I,J),J=1,9),I=1,3)
54    FORMAT(' '///' PRESENT AWT O+M COST',3(/' ',9F14.2))
      DO 55 I=1,3
      DO 55 J=1,9
55    TAWT(I,J)=AWT(I,J)+AWTOM(I,J)
      WRITE(6,56) (( TAWT(I,J),J=1,9),I=1,3)
56    FORMAT(' '///' PRESENT AWT COST',3(/' ',9F14.2))
      WRITE(6,3)
      CALL ZERO
5     FORMAT(' ',///' COMBINATION',4X,9(I6,4X))
      DO 32 I=1,8
      CALL COST(I,1)
      LI=I+1
      DO 32 II=LI,9
      CALL COST(II,2)
      WRITE(6,5) I,II
      CALL GRAVTY(2)
32    CALL ZERO
      DO 33 I=1,7
      CALL COST(I,1)
      LI=I+1
      DO 33 II=LI,8
      CALL COST(II,2)
      LJ=II+1
      DO 33 IJ=LJ,9
      CALL COST(IJ,3)
      WRITE(6,5) I,II,IJ
      CALL GRAVTY(3)
33    CALL ZERO
      DO 34 I=1,6
      CALL COST(I,1)
      LI=I+1
      DO 34 II=LI,7
      CALL COST(II,2)
      LJ=II+1
      DO 34 IJ=LJ,8
      CALL COST(IJ,3)
      LK=IJ+1
      DO 34 IK=LK,9
      CALL COST(IK,4)
      WRITE(6,5) I,II,IJ,IK
      CALL GRAVTY(4)
34    CALL ZERO
      DO 35 I=1,5
      CALL COST(I,1)
      LI=I+1
      DO 35 II=LI,6
      CALL COST(II,2)
      LJ=II+1
```

```
      DO 35 IJ=LJ,7
      CALL COST(IJ,3)
      LK=IJ+1
      DO 35 IK=LK,8
      CALL COST(IK,4)
      LL=IK+1
      DO 35 IL=LL,9
      CALL COST(IL,5)
      WRITE(6,5) I,II,IJ,IK,IL
      CALL GRAVTY(5)
35    CALL ZERO
      DO 36 I=1,4
      CALL COST(I,1)
      LI=I+1
      DO 36 II=LI,5
      CALL COST(II,2)
      LJ=II+1
      DO 36 IJ=LJ,6
      CALL COST(IJ,3)
      LK=IJ+1
      DO 36 IK=LK,7
      CALL COST(IK,4)
      LL=IK+1
      DO 36 IL=LL,8
      CALL COST(IL,5)
      LM=IL+1
      DO 36 IM=LM,9
      CALL COST (IM,6)
      WRITE(6,5) I,II,IJ,IK,IL,IM
      CALL GRAVTY(6)
36    CALL ZERO
      DO 37 I=1,3
      CALL COST(I,1)
      LI=I+1
      DO 37 II=LI,4
      CALL COST(II,2)
      LJ=II+1
      DO 37 IJ=LJ,5
      CALL COST(IJ,3)
      LK=IJ+1
      DO 37 IK=LK,6
      CALL COST(IK,4)
      LL=IK+1
      DO 37 IL=LL,7
      CALL COST(IL,5)
      LM=IL+1
      DO 37 IM=LM,8
      CALL COST (IM,6)
      LN=IM+1
      DO 37 IN=LN,9
      CALL COST (IN,7)
```

```
      WRITE(6,5) I,II,IJ,IK,IL,IM,IN
      CALL GRAVTY(7)
37    CALL ZERO
      DO 38 I=1,2
      CALL COST(I,1)
      LI=I+1
      DO 38 II=LI,3
      CALL COST(II,2)
      LJ=II+1
      DO 38 IJ=LJ,4
      CALL COST(IJ,3)
      LK=IJ+1
      DO 38 IK=LK,5
      CALL COST(IK,4)
      LL=IK+1
      DO 38 IL=LL,6
      CALL COST(IL,5)
      LM=IL+1
      DO 38 IM=LM,7
      CALL COST (IM,6)
      LN=IM+1
      DO 38 IN=LN,8
      CALL COST (IN,7)
      LO=IN+1
      DO 38 IO=LO,9
      CALL COST (IO,8)
      WRITE(6,5) I,II,IJ,IK,IL,IM,IN,IO
      CALL GRAVTY(8)
38    CALL ZERO
      DO 39 I=I,1
      CALL COST(I,1)
      LI=I+1
      DO 39 II=LI,2
      CALL COST(II,2)
      LJ=II+1
      DO 39 IJ=LJ,3
      CALL COST(IJ,3)
      LK=IJ+I
      DO 39 IK=LK,4
      CALL COST(IK,4)
      LL=IK+1
      DO 39 IL=LL,5
      CALL COST(IL,5)
      LM=IL+1
      DO 39 IM=LM,6
      CALL COST (IM,6)
      LN=IM+1
      DO 39 IN=LN,7
      CALL COST (IN,7)
      LO=IN+1
      DO 39 IO=LO,8
```

```
      CALL COST (IO,9)
      LP=IO+1
      DO 39 IP=LP,9
      CALL COST (IP,9)
      WRITE(6,5) I,II,IJ,IK,IL,IM,IN,IO,IP
      CALL GRAVTY(9)
39    CALL ZERO
30    CONTINUE
      STOP
      END


      SUBROUTINE GRAVTY(N)
      COMMON MP
      COMMON CCR(2,9),WT(3,9),CAP(3,9),CI(2, 3,9),POP(3,9),
     *TRC(3,9),TC(3,9),RTRT(3),RCP(3),RTC(3),RPP(3),RTR(3),
     * TC(3,9),RTRT(3),RCP(3),RTC(3),RPP(3),RTR(3),
     * PMP(3,9),CX(9),CY(9),PP(3,9),WTT(3,9),DIS(9),CP(3,9),
     * CCI(2,3,10),COM1(2,3,10),TCC1(2,3,9),TCOM1(2,3,9),
     * PCOM1(2,3,9),ACAP(3,9),ACP(3,9),RACP(3)   ,AWT(3,10),
     * TAWT(3,9),TRT2(2,3,10),TRT3(2,3,10),FX2(2,3),FX(2,3),
     * TRC2(3,9),PMP2(3,9),RPP2(3),PP2(3,9),FX3(2,3),PCC1(
     * 2,3,9),AWTOM(3,10)
      COMMON WT2(3,9),WTT2(3,9),RTC2(3),TC2(3,9)
      DIMENSION  DD(9),WX(9),WY(9)
      DO 101 M=1,2
      DO 101 K=1,3
      SX=0.0
      SY=0.0
      W=0.0
      DO 2 J=1,N
      SX=SX+WTT(K,J)*CX(J)
      SY=SY+WTT(K,J)*CY(J)
2     W=W+WTT(K,J)
      X=SX/W
      Y=SY/W
      LSD=0
6     F=0.0
      G=0.0
      H=0.0
      WRITE(6,12) X,Y
12    FORMAT(' ',10X,2(F10.6,5X))
      DO 1 I=1,N
      DD(I)=((CX(I)-X)**2+(CY(I)-Y)**2)**.5
      WX(I)=WTT(K,I)*CX(I)
      WY(I)=WTT(K,I)*CY(I)
      F=F+WX(I)/DD(I)
      G=G+WY(I)/DD(I)
1     H=H+WTT(K,I)/DD(I)
      X1=F/H
      YI=G/H
```

```
      IF(ABS(X1-X).GT.0.0001) GO TO 3
      IF (ABS(Y1-Y).GT.0.0001) GO TO 3
      GO TO 30
3     LSD=LSD+1
      X=X1
      Y=Y1
      IF (LSD.GT.50) GO TO 5
      GO TO 6
5     WRITE(6,11)
11    FORMAT('          GREATER THAN 50 ITERATIONS')
20    FORMAT(       ' CENTER OF GRAVITY'     ,20X,' X= ',F10.4
     * ,2(H Y= ',F10.4))
30    DO 31 L=1,3
      RTRT(L)=0.0
      RACP(L)=0.0
      RCP(L)=0.0
      RTC(L)=0.0
      RTC2(L)=0.0
      RPP(L)=0.0
      RPP2(L)=0.0
31    RTR(L)=0.0
      DO 100 J=1,N
      DIS(J)=SQRT((CX(J)-X)**2+(CY(J)-Y)**2)
      TC(K,J)=DIS(J)*WTT(K,J)
      TC2(K,J)=DIS(J)*WTT2(K,J)
      RACP(K)=ACP(K,J)+RACP(K)
      RCP(K)=RCP(K)+CP(K,J)
      RTC(K)=RTC(K)+TC(K,J)
      RTC2(K)=RTC2(K)+TC2(K,J)
      RPP(K)=PP(K,J)+RPP(K)
      RPP2(K)=RPP2(K)+PP2(K,J)
100   CONTINUE
      CALL TRT(M,K,RCP(K),RACP(K),10)
      LK=0.0
      RTR(K)=TRT2(M,K,10)+RTC2(K)+RPP2(K)
      IF(RTR(K).GT.FX2(M,K)) GO TO 70
      WRITE(6,71) FX2(M,K),M,K
71    FORMAT(' '///'   TRT2 INDIVIDUAL SUM'/' ',F16.0,
     * 4X,' M= ',I2,'      K= ',I2)
      GO TO 4
72    RTR(K)=TRT3(M,K,10)+RTC(K)+RPP(K)
      IF(RTR(K).GT.FX3(M,K)) GO TO 101
      WRITE(6,73) FX3(M,K),M,K
73    FORMAT(' '///'  TRT3 INDIVIDUAL SUM'/' ',F16.0,
     * 4X,' M= ',I2,'      K= ',I2)
      GO TO 4
70    LK=LK+1
      GO TO 72
4     WRITE(6,20) X,Y
      WRITE(6,25) (TC(K,I),I=1,N)
25    FORMAT(' TOTAL TRN COST'/' ',9F14.2)
```

```
      WRITE(6,26) (CX(JJ),CY(JJ),WTT(K,JJ),PP(K,JJ),CP(K,JJ)
     *,JJ=1,N)
26    FORMAT(         ' COORDINATE (X,Y),TRANSMISSION COST,PUMP
      ING COST, CAPACITY'/9(' ',5F16.2))
     *CAPACITY'/9(/' ',5F16.2))
      WRITE(6,22) (DIS(I),I=1,N)
22    FORMAT(' DISTANCE FROM SOURCE TO CENTER'/
     * ' ',9F14.4)
      CC=CC1(M,K,10)+COM1(M,K,10)
      AA=AWT(K,10)+AWTOM(K,10)
      WRITE(6,27)CC,CC1(M,K,10),COM1(M,K,10),AA,AWT(K,10),AW
     *TOM(K,10)
27    FORMAT(' CONVENTIONAL TRT--CC,CC1,COM1  ADVANCED TRT--
     * AA,AWT,AWTOM'/' ',6(F16.0,4X))
      RTRT(K)=AA+CC
      WRITE(6,21) RTC(K),RPP(K),RTRT(K),M
21    FORMAT(         ' REGIONAL TRANS COST,PUMPING COST,TRT CO
     *ST,TYPE M',/' ',3(F16.2,5X),' M= ',I2)
     * /' ',3(F16.2,5X),' M= ',I2)
      WRITE(6,23) RTR(K)
23    FORMAT(         ' REGIONAL TOTAL'/' ',F16.2)
      LK=LK+1
      IF(LK.EQ.2) GO TO 101
      GO TO 72
101   CONTINUE
      RETURN
      END


      FUNCTION TRM(Q,I,M,N)
      COMMON MM
      COMMON COR(2,9),WT(3,9),CAP(3,9),CI(2, 3,9),POP(3,9),
     *TRC(3,9),TC(3,9),RTRT(3),RCP(3),RTC(3),RPP(3),RTR(3),
     * TC(3,9),RTRT(3),RCP(3),RTC(3),RPP(3),RTR(3),
     * PMP(3,9),CX(9),CY(9),PP(3,9),WTT(3,9),DIS(9),CP(3,9),
     * CC1(2,3,10),COM1(2,3,10),TCC1(2,3,9),TCOM1(2,3,9),
     * PCOM1(2,3,9),ACAP(3,9),ACP(3,9),RACP(3)   ,AWT(3,10),
     * TAWT(3,9),TRT2(2,3,10),TRT3(2,3,10),FX2(2,3),FX(2,3),
     * TRC2(3,9),PMP2(3,9),RPP2(3),PP2(3,9),FX3(2,3),PCC1(
     * 2,3,9),AWTOM(3,10)
      GO TO (16,17,18),MM
17    GO TO (1,2,2),I
16    K=1
      L=16
      GO TO 4
18    GO TO (1,2,3),I
1     K=1
      L=16
      GO TO 4
2     K=6
      L=11
```

```
      GC TC 4
3     K=16
      L=1
4     A=8.55*Q**0.463+2.0436
      B=201.69/154.38
      CC=1524.7*A**1.37949*B
      COM=40.0*(144.9/127.8)
      R=0.05
      F1=  .120444
      F2= .0747619
      TCOM1(N,I,M)=0.0
      TCC1(N,I,M)=CC*(1+F1)**(K+1)/(1+R)**K*L/50
      DO 10 J=1,L
10    TCOM1(N,I,M)=COM*(1+F2)**(J+K)  /(1+R)**(J+K-1)+TCOM1(
     * N,I,M)
      TRM=TCC1(N,I,M)+TCOM1(N,I,M)
      RETURN
      END


      SUBROUTINE TRT(K,I,Q,AQ,J)
      COMMON MM
      COMMON COR(2,9),WT(3,9),CAP(3,9),CI(2, 3,9),POP(3,9),
     *TRC(3,9),TC(3,9),RTRT(3),RCP(3),RTC(3),RPP(3),RTR(3),
     * TC(3,9),RTRT(3),RCP(3),RTC(3),RPP(3),RTR(3),
     * PMP(3,9),CX(9),CY(9),PP(3,9),WTT(3,9),DIS(9),CP(3,9),
     * CC1(2,3,10),COM1(2,3,10),TCC1(2,3,9),TCOM1(2,3,9),
     * PCOM1(2,3,9),ACAP(3,9),ACP(3,9),RACP(3)  ,AWT(3,10),
     * TAWT(3,9),TRT2(2,3,10),TRT3(2,3,10),FX2(2,3),FX(2,3),
     * TRC2(3,9),PMP2(3,9),RPP2(3),PP2(3,9),FX3(2,3),PCC1(
     * 2,3,9),AWTOM(3,10)
      A=184.56/129.84
      B=144.9/110.8
      T=184.56/173.38
      S=144.9/102.5
      GO TO (16,17,18),MM
17    GO TO (1,2,2),I
16    M=1
      L=16
      GC TO 4
18    GC TO (1,2,3),I
1     M=1
      L=16
      GC TC 4
2     M=6
      L=11
      GC TO 4
3     M=16
      L=1
4     GO TC (5,6),K
5     CC=EXP(13.0554)*Q**(.62539)*T
```

```
      COM=10.0**(4.5046+0.6498*ALOG10(Q))*S
      GO TO 7
6     CC=EXP(13.4586)*Q**(.6456)*T
      COM=10.0**(4.6720+0.6023*ALOG10(Q))*S
7     R=0.05
      TSC=EXP(-2.05283)*AQ**.776102*10.**6*A
      TSCO=EXP(4.14078)*AQ**.692928*365*B
      RC=EXP(-1.62467)*AQ**.508007*10.**6*A
      RCO=EXP(3.8994)*AQ**.728564*365*B
      AS=EXP(-0.712259)*AQ**1.10744*10.**6*A
      ASO=EXP(3.71221)*AQ**.778987*365*B
      AW=TSC+RC+AS
      AWTO=TSCO+RCO+ASO
      F1=  .104214
      F2=  .0747619
      AWTOM(I,J)=0.0
      COM1(K,I,J)=0.0
      AWT(I,J)=AW*(1+F1)**(M+1) /(1+R)**M *L/25
      CC1(K,I,J)=CC*(1+F1)**(M+1) /(1+R)**M*L/25
      DO 10 N=1,L
      AWTOM(I,J)=AWTOM(I,J)+AWTO*(1+F2)**(N+M  )/(1+R)**(N+M
     * -1)
10    COM1(K,I,J)=COM1(K,I,J)+COM*(1+F2)**(N+M  )/(1+R)**(N+
     * M-1)
      TRT2(K,I,J)=CC1(K,I,J)+COM1(K,I,J)
      TRT3(K,I,J)=TRT2(K,I,J)+AWT(I,J)+AWTOM(I,J)
      RETURN
      END


      FUNCTION PMG(Q,I,M,N)
      COMMON MM
      COMMON CCR(2,9),WT(3,9),CAP(3,9),CI(2, 3,9),POP(3,9),
     *TRC(3,9),TC(3,9),RTRT(3),RCP(3),RTC(3),RPP(3),RTR(3),
     * TC(3,9),RTRT(3),RCP(3),RTC(3),RPP(3),RTR(3),
     * PMP(3,9),CX(9),CY(9),PP(3,9),WTT(3,9),DIS(9),CP(3,9),
     * CC1(2,3,10),COM1(2,3,10),TCC1(2,3,9),TCOM1(2,3,9),
     * PCOM1(2,3,9),ACAP(3,9),ACP(3,9),RACP(3)   ,AWT(3,10),
     * TAWT(3,9),TRT2(2,3,10),TRT3(2,3,10),FX2(2,3),FX(2,3),
     * TRC2(3,9),PMP2(3,9),RPP2(3),PP2(3,9),FX3(2,3),PCC1(
     * 2,3,9),AWTOM(3,10)
      GO TO (16,17,18),MM
17    GO TO (1,2,2),I
16    K=1
      L=16
      GO TO 4
18    GO TO (1,2,3),I
1     K=1
      L=16
      GO TO 4
2     K=6
```

```
      L=11
      GO TO 4
3     K=16
      L=1
4     CC=76300.0*C**(.7682)*(201.69/154.38)
      COM=1.6103*Q**(.73743)*10.0*(144.9/122.8)*365
      R=0.05
      F1= .104214
      F2= .0747619
      PCOM1(N,I,M)=0.0
      PCC1(N,I,M)=CC*(1+F1)**(K+1) /(1+R)**K*L/25
      DO 10 J=1,L
10    PCOM1(N,I,M)= PCOM1(N,I,M)+COM*(1+F2)**(J+K   )/(1+R)**
     *(J+K-1)
      PMG=PCC1(N,I,M)+PCOM1(N,I,M)
      RETURN
      END


      SUBROUTINE ZERO
      COMMON MM
      COMMON CCR(2,9),WT(3,9),CAP(3,9),CI(2, 3,9),POP(3,9),
     *TRC(3,9),TC(3,9),RTRT(3),RCP(3),RTC(3),RPP(3),RTR(3),
     * TC(3,9),RTRT(3),RCP(3),RTC(3),RPP(3),RTR(3),
     * PMP(3,9),CX(9),CY(9),PP(3,9),WTT(3,9),DIS(9),CP(3,9),
     * CC1(2,3,10),COM1(2,3,10),TCC1(2,3,9),TCOM1(2,3,9),
     * PCOM1(2,3,9),ACAP(3,9),ACP(3,9),RACP(3)   ,AWT(3,10),
     * TAWT(3,9),TRT2(2,3,10),TRT3(2,3,10),FX2(2,3),FX(2,3),
     * TRC2(3,9),PMP2(3,9),RPP2(3),PP2(3,9),FX3(2,3),PCC1(
     * 2,3,9),AWTOM(3,10)
      DO 1 I=1,2
      DO 1 J=1,3
       FX2(I,J)=0.0
1     FX3(I,J)=0.0
      RETURN
      END


      SUBROUTINE COST(I,J)
      COMMON MM
      COMMON CCR(2,9),WT(3,9),CAP(3,9),CI(2, 3,9),POP(3,9),
     *TRC(3,9),TC(3,9),RTRT(3),RCP(3),RTC(3),RPP(3),RTR(3),
     * TC(3,9),RTRT(3),RCP(3),RTC(3),RPP(3),RTR(3),
     * PMP(3,9),CX(9),CY(9),PP(3,9),WTT(3,9),DIS(9),CP(3,9),
     * CC1(2,3,10),COM1(2,3,10),TCC1(2,3,9),TCOM1(2,3,9),
     * PCOM1(2,3,9),ACAP(3,9),ACP(3,9),RACP(3)   ,AWT(3,10),
     * TAWT(3,9),TRT2(2,3,10),TRT3(2,3,10),FX2(2,3),FX(2,3),
     * TRC2(3,9),PMP2(3,9),RPP2(3),PP2(3,9),FX3(2,3),PCC1(
     * 2,3,9),AWTOM(3,10)
      COMMON WT2(3,9),WTT2(3,9),RTC2(3),TC2(3,9)
      DO 10 K=1,3
```

```
      CX(J)=CCR(1,I)
      WTT(K,J)=WT(K,I)
      WTT2(K,J)=WT2(K,I)
      ACP(K,J)=ACAP(K,I)
      PP2(K,J)=PMP2(K,I)
      CP(K,J)=CAP(K,I)
      PP(K,J)=PMP(K,I)
      CY(J)=CCR(2,I)
      DO 10 M=1,2
      FX2(M,K)=FX2(M,K)+TRT2 (M,K,I)
10    FX3(M,K)=FX3(M,K)+TRT3(M,K,I)
      RETURN
      END
/*
```

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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