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THE EFFECT OF DATA LIMITATIONS ON THE APPLICATION OF SYSTEMS ANALYSIS TO WATER RESOURCES PLANNING IN DEVELOPING COUNTRIES

by Luis Ernesto Garcia-Martinez

COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO
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THE EFFECT OF DATA LIMITATIONS ON THE APPLICATION OF SYSTEMS ANALYSIS TO WATER RESOURCES PLANNING IN DEVELOPING COUNTRIES

Water Management Technical Report No. 7

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Optimum Utilization of Water Resources:
With Special Emphasis on Water Delivery
and Removal Systems and Relevant
Institutional Development

Prepared by

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May, 1971

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ABSTRACT

THE EFFECT OF DATA LIMITATIONS ON THE APPLICATION OF SYSTEMS ANALYSIS TO WATER RESOURCES PLANNING IN DEVELOPING COUNTRIES

This study emphasizes the importance of the systems approach to account for the main developing goals in the planning of water resources projects in developing countries. Its main concern is whether this technique is still applicable considering the many uncertainties caused by data limitations.

The objectives of the study are to identify the factors that produce the greatest degree of uncertainty in terms of a given economic measure of project performance. Three major areas are investigated: the effect of the choice of different types of model, the effect of the uncertainties introduced by the estimation of the parameters of the model, and the significance of policy guidelines, including the economic model chosen for the economic appraisal of projects.

The approach followed in this study was to analyze a real project in a developing country (Guatemala, Central America) in order to give relevance to it, to gain insight into the problem by experimental techniques, and on the basis of that, obtain conclusions of general applicability for the problem studied.

The results of this study indicate that the use of stochastic systems analysis for planning water resources projects in developing countries is not an unnecessary sophistication, but a useful tool. The planner, however, should be aware of the factors that produce the uncertainties with the greatest economic effect, and of the nature of this effect. The effect produced in the area of choosing policy

guidelines, for example, appears to be of greatest importance, closely followed by the effect of the choice of the model.

It was found that the use of a deterministic optimization model, by itself, can cause unfavorable economic consequences. Similarly, an investigation of the economic effect produced by the type II error involved in the choice of a model for stochastic streamflow simulation, can be used to counteract the effect of data limitations in the selection of such a model. It was also found that the use of a broken-line model for streamflow simulation, can be a useful operational tool in the face of uncertainty in the autocorrelation structure of streamflows.

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CHAPTER I

INTRODUCTION

There is no generalized consensus for a definition of the term "systems analysis." When applied to water resources planning, various definitions of the term have been given, some being more encompassing than others.

This work deals with the application of systems analysis to water resources projects in developing countries. Therefore, it was deemed useful to review briefly the role that such projects can play within the development efforts of a country, and the potential advantages of systems analysis to determine the scale of development of these projects so that they may contribute more effectively toward the goals of such efforts.

This introduction also serves the purpose of defining the problem involved in the successful application of systems analysis for water resources planning in developing countries. Finally, a brief description is given of the approach used to investigate the problem and to arrive at the conclusions and recommendations offered at the end of this dissertation.

Systems Analysis

In general terms a system can be defined as an aggregation of parts (concepts or objects) which are interrelated by some kind of interdependence. In this sense, it can be as broad as nature itself. Take for example the water within a region, which could be arbitrarily defined say in terms of political boundaries, as in a country. The water may be distributed in several basins, all streams within each basin being

interrelated; the ground water within each basin also being interrelated with the surface water. But the basins within this region may also be interrelated with each other and with other regions by the hydrologic cycle. This inter-regional relationship may also result because the artificial political boundaries of the region will not usually follow the natural boundaries of the basins. Water in its behavior is also related to physical characteristics of the basin, such as underlying geological formations, type of soils, vegetative cover, and morphology.

Water is also used by living "objects" in their vital processes. As a resource, man uses water for a number of beneficial purposes, for example to grow or produce other kinds of "objects" which are also interrelated to each other and again to other types of "objects." To make use of the water, man builds a series of physical features which introduce more of these relationships. The beneficial uses of water are certainly related to man's institutions such as politics, the economic structure, or society itself. Thus a water resources system has many aspects besides the hydrologic; it is also physical, biologic, socio-political, legal and economic.

Traditionally, attention has been given to the different components of such a system, but seldom is complete and systematic consideration given to the interrelationships existing among these components. These relationships have been at most acknowledged or treated only in a qualitative way because the methods of analysis were not adequate for that purpose. Lately, a great effort has been made to adapt certain mathematical tools developed for other disciplines to the analysis of water resources systems to explicitly account for these interrelationships. The use of these tools, however, requires that a mathematical model of

the real system be made. For various reasons, such a model inevitably falls short of the real world. Only a few elements and relationships are accounted for in the model.

The systems approach is basically that of the scientific method. Hillier and Lieberman (1)* give as four the number of steps involved. They can be described as follows:

1. Formulating the Problem

This step involves the identification of those elements that are going to be included as part of the system, the proper identification of the interrelationships between them, the definition of the objective and the constraints that could limit the solution to the problem, and the identification of the elements that can be modified in order to attain the objective. It is a basic part of the processes which can determine the success or failure of the analysis in terms of the application of its results to the real world. It is Hall and Dracup's (2) "art" portion of Systems Engineering that should be attempted with a thorough knowledge about the elements and the relationships that will be considered as part of the system.

2. Constructing the Model

An idealized representation of the essential features of the problem must be made (in this case in terms of mathematical expressions, i.e., a "mathematical model") obviously making some simplifications and assumptions. Therefore, care must be taken to assure that the model is still a valid representation of the problem (a thorough knowledge of the system under consideration is also necessary for this). A very important

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* Numerals in parenthesis refer to corresponding items in the List of References.

part of this mathematical model is the objective function, i.e., a mathematical expression that can be used to quantify the effect that alternative courses of action will have upon the objective and thus rank them accordingly.

3. Deriving a Solution

Once the model has been built, obtaining a solution for the problem under consideration is not only a matter of cranking it up through a computer. Any modification to the model must be made before its results are implemented, i.e., all possible shortcomings, errors or oversights of the model should be identified in advance. Data requirements should be analyzed for compatibility with data availability. The relative importance of different types of data should be explored in order either to obtain the information or to modify the model.

4. Implementation of the Solution

Usually this implementation will not be a decision of the planner, but of those individuals at the higher levels of the government. Therefore, it is of extreme importance that the model should allow one to properly answer in a quantitative way the consequences of alternative courses of action. Finally, solutions for the model will only be approximations to the solution in the real world. However, they will provide a better guide for action because a decision reached with "more knowledge" has a better chance of being correct than a decision based on "less knowledge" (3).

The systems analysis approach in water resources is then both a way of viewing things (aggregation of interrelated objects) and a way of dealing with these things as we see them (the use of the mathematical

tools and mathematical models to explicitly account for these interrelationships).

Systems Analysis for Developing Countries

The current economic meaning of the term "developing countries," under which a large number of nations of the world are grouped, is simply that the annual per-capita income of their population is very low. This index, however, does not reflect the real situation and many problems of developing economies. In many countries for example, the issue of income redistribution among clearly differentiable sectors of the population may be as important as to increase this index of per-capita income.

Developing countries, however, in general do have the potential human and natural resources to obtain a degree of development in accordance with their possibilities (i.e., higher than the present, although maybe not at the highest levels now exhibited by the more "advanced" countries of the world) and with a more equitable distribution of the national income among their population. What is needed then, is to apply policies so as to distribute the available economic resources in the most efficient way to obtain a particular objective. However, some very important "bottlenecks" exist which make this task much more difficult than it may appear. The more important bottlenecks that restrain development have been identified as the lack of <u>training of the human resources</u> of a country, and the lack of <u>adequate institutions</u> through which man can utilize the natural resources at his disposition (4). From the point of view of the economic role that a public investment can play in the developing efforts of a country, however, other

aspects should also be considered. These aspects have been reviewed (5) as being the following:

1. Scarcity of capital for investment.
2. Difficulties with the balance of payments: Most developing countries are "primary producers." They export raw materials to developed countries and import from them most of the needed producer and consumer goods. Usually, a few products for which a country has a comparative natural advantage (coffee, cotton, sugar, etc.) are the main source of hard foreign currency with which to buy the required producer and consumer goods. The economy's welfare is thus tied to the price of these exports which is subject to the fluctuations of the world's demand and supply. Moreover, the nature of these exports is such that their demand expands slowly and then there is always an increasing trend to use synthetic substitutes for raw materials. The price of consumer and producer goods, however, tends to increase as the economies of the more developed countries grow. Governments are then forced to set quantitative restrictions on foreign exchange, thus introducing imperfections into the foreign exchange market.
3. A high annual growth rate of the population: This will have a depressing effect upon the forces that may be set in motion in order to increase per-capita incomes, causing a tendency to return to low-level equilibrium points.
4. A high degree of unemployment, as well as an unproductive population surplus in the agricultural sector: This last group of persons is underemployed and although they work along with the

others, their efficiency is low and the same production could be obtained if this surplus labor were removed from the land.

The removal of these economic bottlenecks constitutes the main goals expressed in most development plans (5), namely:

1. To achieve higher rates of economic growth.
2. To achieve a balance of payments equilibrium.
3. To obtain a more equitable distribution of income.
4. To improve the employment situation.

Of all these goals, the achievement of higher rates of economic growth is generally given priority. Strategies for economic growth favor a capital-intensive industrial expansion (import substitution) against a labor-intensive agricultural expansion (export expansion)(5). Because the supply of capital is limited, investment in those areas with strongest external economies are favored. However, if industrialization is crucial to development, agriculture plays an important supporting role in this process by feeding the labor force and obtaining the necessary foreign exchange. A capital-intensive policy increases the rate of savings and capital accumulation producing an increase in the per-capita income at some point in the future. This reveals preoccupation for the future generations, but governments should be concerned for the present generation as well. On the other hand, not doing anything for the unemployed population is open to moral questioning, as well as it represents political suicide. Governments, then, usually favor labor-intensive production techniques in the agricultural sector while favoring capital-intensive investments in other sectors of the economy (5).

A large percentage of the investments in developing countries comes from the public sector (government). Public projects should be designed

so as to accomplish the development aims of the country. Water resources projects are usually public projects that possess certain characteristics that may be advantageously used to make investments in that sector according to these development aims. These characteristics are:

1. Water resource projects are capital-intensive as compared to other types of projects.
2. They exhibit strong external economies.
3. Empirical studies show that comprehensive river basin water resources projects appear to promote successful agricultural development in the area, thus providing the necessary support for industrialization as well as favoring labor-intensive activities in the agricultural sector (6).
4. Abundant electrical energy at low cost by itself may or may not encourage industrialization. So far, empirical evidence shows that it may tend to encourage the establishment of light industry, but that there may be other factors with equal or more weight (6).

Thus, if a country has set forth certain economic objectives for development, the investment in the water resources sector must be evaluated as to how much it will contribute to the fulfillment of those objectives. The systems approach allows for the ranking of alternative projects and for the finding of an "optimal" scale of development for these projects according to their contribution to these objectives.

The Problem Investigated and Objectives of This Study

The systems analysis approach for the planning of water resources projects has the advantage of joining the engineering and economic aspects, thus allowing for the search for a "best" solution in terms of

certain economic objectives that might be specified. Because the scarcity of capital for investment is one of the general characteristics of developing countries, the design and evaluation of projects, in terms of their role in the development efforts of a country, is of great importance. Thus, a systems analysis approach would seem very attractive.

The data required for the application of systems analysis to water resources problems may include hydrometeorological records, cost and benefit functions, economic loss functions, and demand functions. Costs and benefits cannot be estimated with absolute reliability, as was found by Altouney (7) in his study of actual and estimated costs and benefits from 103 projects in the United States; the main reason being that they are based on projections into the future. But even if they could be so estimated, an economic measure of the performance of a system - such as the present value of net benefits - is a random variable rather than a constant, since it is a function of other random variables such as streamflows and water requirements.

On the other hand, the use of systems analysis requires the construction of a model, or idealized representation of the problems under consideration. The objective function that measures the relative merit of different courses of action and the mathematical description of the most important characteristics of the streamflow series are examples of very important components of this general model. All these circumstances cause the designs to be subject to a great deal of uncertainty. This uncertainty may be due to natural causes, i.e., due to the stochastic nature of the variables involved; it may be due to the form of the model used to represent the "real world"; it may be due to a failure to estimate the model parameters with precision; or it may be due to any combination of these causes.

Unfortunately, the data requirements for the application of systems analysis to the design of water resources projects may seem prohibitive for countries where even the application of the "traditional" methods of analysis require a great number of approximations and assumptions. Usually data are limited, and useful information has not and is not being obtained and compiled because the over-simplified methods do not require it. Sometimes, even recognizing that this simplistic approach may lead in some instances to dangerous under-designs or wasteful over-designs, projects are designed without the benefit of certain data and information because the designer must wait too long a time for these data to be collected, or because the importance of these data in the design is not apparent to the planner.

The danger of under-designing is dealt with to a certain extent by the use of arbitrary safety-factors, but these are not entirely satisfactory. Under these conditions, a project that appears physically and financially feasible may contribute very little towards the economic aims of the country, or, worst, may even be detrimental to those aims.

The problem of uncertainty is thus of particular importance in developing countries, where all these estimates have to be made based on a limited amount of data, decreasing their reliability. Therefore, a tendency toward sophistication in the methods of design in an attempt to keep up to date with the latest developments of the art, is not justifiable if inadequate data will make the results as unreliable as those being currently obtained: "garbage-in-garbage out." In this respect, King (8) in his review of the World Bank's methods of project appraisal states that a "...healthy skepticism is a cardinal virtue."

He goes on to say the Bank considers that:

> This skepticism must be applied to the economic technical, institutional and financial aspects of the project appraisal, beginning with a questioning of the basic statistical data to make sure that a false sense of accuracy has not been reached through the application of sophisticated techniques of analysis to questionable basic data.

Although this problem has special meaning for developing countries, it is by no means exclusive to them. For example, an AWRA discussion panel (9) pointed out that because model builders have usually been more preoccupied with the computational model itself, they have "leap-frogged" the data problem, and that "the data, usually inferred as available when needed...deserves more attention, and there seems plenty of employment opportunities for the systems analyst here" (9).

Is it worthwhile then, to try to apply these relatively new techniques in developing countries? Should they be dismissed because of inadequate data? It seems like a vicious circle: the systems approach would be very useful, but cannot be applied because there are not enough data; and data are not obtained because the "tradional" methodology cannot benefit from them and does not need them. So, the scarce resources of a country may be diverted from projects that fit better into the developing effort in favor of others whose only merit is perhaps an apparent financial justification. Fortunately, there are some bright spots in this otherwise gloomy picture:

1. Some information does exist, although perhaps not in the precise form required for its utilization in systems analysis. Some effort is needed to transform it for that purpose.
2. In some instances, it may be economically worthwhile to wait for a given period of time in order to collect certain data

rather than to base designs on extremely short records or, conversely, it may not be necessary to wait too long in order to obtain an acceptable design. For example, Moss (10) found that for those stream gaging stations whose purpose is to provide a record to be used for the design of a water conservation reservoir, the optimum length of record was nine years if the project was to be initiated right after the period of gaging, and up to the initiation of the project if it were delayed by some reason, to an upper limit of 56 years.

3. Even if records--such as hydrologic--are of short duration, there are techniques that make it possible to extract (not create) a maximum amount of information. For example, the unreliability of the statistics estimated from a short record may be diminished by using generalized statistics obtained from physical and climatic factors by the use of multiple regression analyses (11), (12).

However; the investments to be made in collecting, transforming or compiling these data should be made as rationally as possible. Young, Orlob, and Roesner (13) pointed out that the variability of an economic measure of system performance (such as the present value of net benefits) depends not only upon the variability of each economic and hydrologic parameter used in the model, but also upon the response of the optimization model to unit changes in those parameters. The efforts (i.e., the investments in data programs) should then be directed towards reducing the variability of those elements with respect to which the response of the model is the largest, provided this variability

could be reduced by such measures. Additional expenditures for the estimation of parameters whose variability cannot be significantly reduced, and/or will not produce a significant response of the optimization model, cannot be justified.

The problem can thus be summarized as follows:

1. The systems approach can be a powerful tool for planning water-resources projects within the framework of the development efforts of a country.
2. Data limitations, however, increase the uncertainties in the model to be applied.
3. Which are the factors that introduce the greatest relative degree of uncertainty? Are they related to natural causes, to the choosing of the model or parts of it, or to the estimation of the model parameters? Can some of these uncertainties be coped with by the use of safety factors? If so, which would be the most rational way to determine them?

The answer to this last group of questions is the general objective of this research. Particular goals are:

1. To determine the relative effect upon the "maximum" present value of net economic benefits of factors such as:
   a. The choice of a deterministic linear optimization model.
   b. The choice of deterministic demands, and of stochastic correlated and uncorrelated supply and irrigation demands.
   c. The choice of the model to represent the autocorrelation structure of the stochastic component of streamflow series.
   d. The effect of errors in the estimation of the basic economic and hydrologic factors once a model has been chosen.

e. The effect of policy guidelines which may be expressed as constraints in the optimization process.

2. To explore the possibilities of developing operational streamflow simulation procedures for the use of a broken-line model when the use of such a model is considered appropriate, or as an alternative to autoregressive models for cases in which the latter may be considered to be inadequate.

The Approach Used

The approach chosen for this research is to analyze a real situation in a developing country in order to give relevance to it, to gain insight into the problem by experimental techniques, and on the basis of that, obtain conclusions of general applicability for the problem being studied: the effect of data limitations on the application of systems analysis to water-resources planning in developing countries.

A model considered to be the most adequate one based on the present state of the art was chosen regardless of data requirements. In this model the stochastic nature of both supply and demand sequences is taken into account. Under these circumstances, the simulation technique is the most appropriate one for the systems analysis. This technique involves the generation of "equally likely" sequences of both supply and demand, either independently or correlated. The system under consideration is then defined by giving values to the design variables (such as the reservoir size, for example) and its response to each of the "equally likely" generated sequences is obtained. This response can be the present value of net benefits, as obtained by the objective function.

A probability distribution of responses is developed for the set of values given to the decision variables. A statistic of this distribution, such as a value with a given probability of being exceeded, can be "optimized" by assigning different sets of values to the design variables and repeating the procedure each time. To reduce the number of such trials, an optimization routine can be attached to the simulation program. The number of the trials may also be reduced if a preliminary estimate of the "optimum" value of the design variables is obtained prior to starting with the simulation.

The use of mathematical "one shot" optimization models (such as linear programming, for example) for preliminary screening (i.e., elimination of the less promising alternatives to be considered in a complex multi-site water-resources system) has been advocated by Hufschmidt and Fiering (14). This approach has been successfully applied, as reported by Loucks (15). He found, however, that if mean flows were used in these models and if continuity was assumed (i.e., the storage volume at the end of a year equals the volume at the beginning of next year), they were of little value for preliminary screening. Better results were obtained when the continuity condition was not assumed and better yet, by using stochastic models. Since the latter models required more computer time, they were not applied until a first screening was done using the discontinuous deterministic models.

A first approximation to the "optimum" values of the design variables was thus obtained in the research described herein by using a discontinuous deterministic linear programming model. This was also done for the following reasons:

1. Data limitations in developing countries may increase the temptation to define "just a couple of points" in the cost, benefit, and loss functions, assuming these to be linear, and to use mean flows and deterministic demands in a linear programming model. The results of this model often may be accepted without further consideration of the effect of such assumptions or whether it is worthwhile to include all these "additional complexities" in the analysis.
2. Furthermore, McLaughlin has stated (16) that:

> One of the main dangers of preliminary analysis is the possibility of the approximations and assumptions causing a plan or component to be discarded when a more accurate analysis would indicate that it should be considered for further study. The discarded item can be said to be biased out of future consideration. The most common cause of bias is leaving important features out of the initial configuration, but with linear programming bias can be expected from two additional sources: the use of periods that are too long for reasonable description of hydrology or water use and the neglect of stochastic effects.

3. The use of a deterministic linear programming model for a first approximation, will then aid in exploring these matters.

Taking into account that the design of the project using "conventional" methods gives a starting point and allows for the investigation of the effects of such an approach as compared with the deterministic and stochastic systems approach, these steps were thus followed:

1. Selection of an actual problem in a developing country, obtaining of data, and derivation of a "conventional" benefit-cost economic evaluation.
2. Modification of the economic evaluation to take into account special characteristics of developing economies, as proposed by Mobasheri (6).

3. Obtaining a first approximation to the "optimum" by using a discontinuous deterministic linear programming model.
4. Analysis of both supply and demand sequences, in order to select a model by which to generate the "equally likely" sequences to be used in the simulation.
5. Obtaining a better approximation to the "optimum" by simulation using stochastic supply and demands.
6. Analysis of the effect of the different types of uncertainties introduced by data limitations.

CHAPTER II

REVIEW OF LITERATURE AND METHODOLOGY

In order to follow the steps mentioned at the end of Chapter I, existing methodologies were used either as they have been proposed in the past or modified when the author considered it necessary. These methodologies were used as research tools. This chapter describes these tools in its first four sections: economic evaluation, supply, requirements, and the objective function. The last section on the relative importance of the planning data reviews the existing literature on the particular problem which constitutes the main topic of this dissertation.

Economic Evaluation

Economic evaluation is by no means the only type of feasibility study that must be made on a proposed project. Warner (17), for example, considers six areas of analysis: technical, economical, financial, sociological, political and administrative. At a national level, i.e., from the point of view of a national planning agency, the economic, financial, and political aspects are of main concern, the other aspects corresponding to other levels of planning according to the nature of the project. Economic evaluation of a water resources project is usually accomplished through a benefit-cost analysis. Traditional benefit-cost analysis as practiced in the more developed countries involves certain assumptions that cannot hold in developing economies. Several authors have proposed different models to account for these differences, although they require more data and make use of concepts

which are not included in the traditional procedures used by some international financing institutions. The traditional procedure used by most developing countries and an alternative method as proposed by Mobasheri (6) are reviewed in this section.

Benefit-Cost Analysis: Economic evaluation of a project is obtained through an economic feasibility study, which makes use of a Benefit-Cost Analysis:

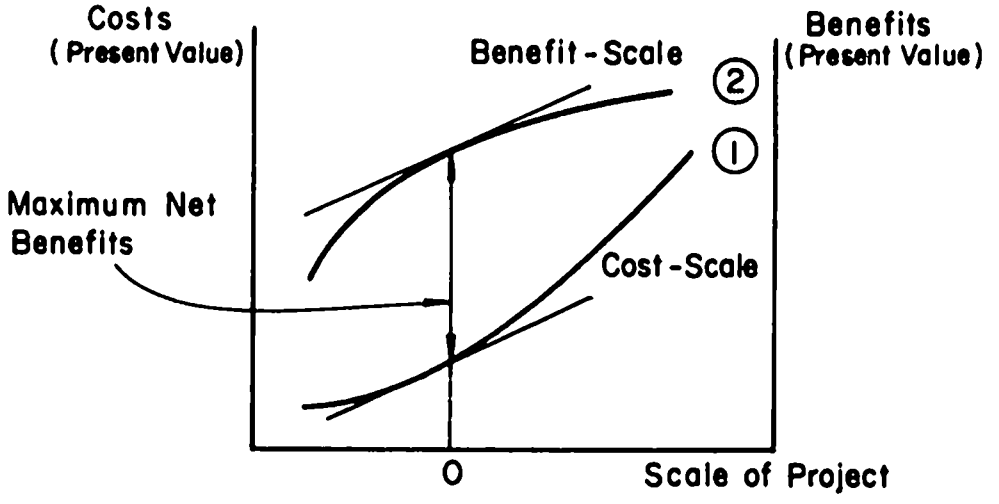

Figure 2.1. Optimum Scale of a Project

The optimal level of development of a project is where the tangents to curves 1 and 2 are parallel (18). At this point, for a unit increment of the scale of the project the marginal cost equals the marginal benefit. To the left of 0 , marginal cost is less than marginal benefit, so it pays to increase the scale to the point where marginal cost and marginal benefit are equal. To the right of point 0 , marginal costs increase and marginal benefits decrease, so additional incremental units of scale are not worth their cost.

The economic evaluation looks not only at the direct monetary benefits and costs to the investor, but at the total national benefits and costs "to whom they may accrue" (18). It is not an analysis for justification (like financial feasibility), but an analysis to evaluate the project and assign a degree of desirability to it, compared to other projects, in terms of how well it contributes to the economic aims of a country. If a competitive market system is functioning (i.e., there are reasonably full levels of employment, there exists mobility of capital and labor forces, and competitive conditions exist throughout the economy) then the total national economic benefits of a project can be ascertained by the real output of the project, valued at observed or simulated market prices, and the total national economic cost of a project can be ascertained by the real inputs used in the project, also valued at observed or simulated market prices (19). Then, there is no need to include indirect benefits and costs into the B-C analysis as used in more developed countries for economic evaluation of projects. Also, in the more developed countries the basic economic rationale justifying public expenditures for water resources development is the criterion of national economic increase, leaving to the market the allocation of benefits among the population. In developing countries, however, these conditions do not exist (6). Unemployment and underemployment, shortage of hard foreign currency and scarcity of capital create market imperfections and the market prices do not reflect social preferences. On the other hand, the distribution of benefits cannot be left to the market and the influence of the project upon things such as reinvestment of portions of these benefits, rate of capital accumulation and rate of economic growth, is one of the reasons for justifying

public expenditures in water resources. So the B-C analysis, as performed in the more developed countries for economic evaluation of projects is not considered adequate for the same purpose in developing countries (6)(20).

Traditional Procedure: Usually, most funds for water resource projects are sought abroad as foreign currency loans. Although international financial institutions like the World Bank (8) are interested in questions such as the effective contribution of a project to the development of a sector of the economy which deserves priority, and the effects upon the balance of payments, these aspects usually are considered only in a qualitative manner. Despite criticism on this aspect (21) the "internal-rate-of-return rule"* is advocated for project appraisal and a great deal of weight is placed upon the appraiser's judgement. The World Bank approach is described by King (8) from which the following excerpts are made:

> The Bank's experience has taught that in project appraisal... healthy skepticism is a cardinal virtue...Not withstanding this skepticism, the Bank does not take the relatively narrow viewpoint of the conventional creditor. It expects, of course, that each loan will be repaid in accordance with its terms, but it is just as interested in the issue of whether use of the borrower's credit for the particular project under investigation is justifiable in terms of what it can be expected to contribute to the over-all development of the country.
>
> A first indication of the economic justification of a project can be obtained by calculating an economic rate of return for it...distorting factors often make an appraisal, based on actual prices, of the economic merits of a project incomplete and inaccurate. Sometimes enough information is available on the real, undistorted costs to the economy of the main resources required so that appropriate adjustment can be made of the values

---

* This rule accepts any project for which the internal rate of return (the discount rate which makes the present value of benefits equal to the present value of costs) is greater than a given rate selected by some criteria.

> of costs and benefits arrived at by the use of actual prices. In many cases, however, only qualitative adjustment is possible... the total costs and benefits of a project often cannot be determined quantitatively, and a sound economic view of projects must always depend to some extent on the judgement of those carrying out the appraisal.

For these reasons, usually only direct costs and benefits are quantified in economic analyses. Because capital is scarce, however, an effort is made to account for the social opportunity cost by using an internal rate of return higher than the market interest rate (22). Nevertheless, market prices are used for the other factors and only qualitative considerations are made of this aspect. The net effect is that although national development plans state goals such as income redistribution, increase in national savings, leveling of the balance of payments, and the provision of employment opportunities in the agricultural sector, the economic evaluation of projects is made based on a model which takes explicitly into account only the financial productivity of the invested funds. In view of this inadequacy, more than one author has proposed models to explicitly account for the goals of the country. One such model is reviewed in the following section. It was used in this investigation as an example of the alternatives available to the traditional approach and to see what types of limitations would be encountered in the evaluation of its parameters.

Alternative Model: The optimum scale of development for a project, as it has been defined (6), is the "optimum combination of design variables which maximizes the value of a given objective function subject to a set of imposed constraints, invariant parameters, and constants." In a developing country, this objective function should meet certain desirable requisites (6):

1. The value given by the objective function, should be the present value of net economic benefits.
2. It should take into consideration the main concerns for economic development, which in most developing countries are multiple. The main concerns are, for example, to achieve higher rates of economic growth, to achieve a balance of payments equilibrium, to obtain a more equitable distribution of income, and to improve the employment situation (6).
3. It should take into consideration the existence of an imperfect market due to desequilibria such as unemployment, shortage of hard foreign currency, and shortage of capital for investment.

A criterion has been proposed (6) which, evolving from the traditional benefit-cost analysis, provides an objective function which takes into account the social benefits and costs of a project and reflects the national goals and economic characteristics of developing countries. This criterion is as follows (6):

1. To reduce costs and benefits to a common point in time. Two discount rates are used instead of the market interest rate, which in developing countries is very high. These are:
   a. A social discount rate r, which is a measure of the social time preference (i.e., consume later than now). This is deduced based upon a simplified social welfare function and computed as equal to the rate of change of per capita income.

$$r = g - \ell \qquad (2.1)$$

in which
r = social discount rate
g = rate of growth of the total national product
ℓ = rate of growth of the population

b. <u>A social capital productivity rate</u> θ_g , which reflects the opportunity cost of capital, i.e., the benefits which will not be realized because of investing the capital in the project under consideration.

$$\theta_g = \sum_{i=1}^{n} d_i \frac{\rho_i}{r} + (1 - \sum_{i=1}^{n} d_i)U_c \tag{2.2}$$

in which θ_g = social capital productivity rate

d_i = R_i/total government budget

$$\left\{ \begin{array}{l} R_i = I_i - F_i \quad \text{when} \quad F_i - I_i < 0 \\ \\ 0 \quad \text{when} \quad F_i - I_i \geq 0 \end{array} \right\} \tag{2.3}$$

$$I_i = \frac{g_i - \alpha_i \ell_i - \varepsilon_i}{\beta_i} K_i \tag{2.4}$$

$$g_i = \alpha_i \ell_i + \beta_i k_i + \varepsilon_i \tag{2.5}$$

in which ℓ_i = rate of labor growth in sector i

k_i = rate of capital accumulation in sector i

$$F_i = (1-\gamma_i)[(1-a_i-m_i)\beta_i X_i - \delta_i K_i]$$

α_i , β_i , and ε_i are coefficients of a Cobb-Douglas production function for X_i

$$X_i = A_i L_i^{\alpha_i} K_i^{\beta_i} e^{\varepsilon_i t} \tag{2.6}$$

in which X_i = value of the annual gross production in sector i of the economy

A_i = constant of proportionality

$\left.\begin{matrix}\alpha_i \\ \beta_i\end{matrix}\right\}$ constant production coefficients

ε_i = rate of technological progress in sector i

L_i = number of laborers in sector i

K_i = value of total capital investment in sector

The remainder of the parameters involved in Eq. (2.2) are:

γ_i = tax rate on profit made in sector i

a_i = value of intermediate goods used in sector in terms of proportion of the value of production of sector i

m_i = excise tax rate on products produced in sect(i

δ_i = capital depreciation rate in sector i

ρ_i = avge. rate of return on capital invested in sector i

U_c = social value of present consumption

n = number of sectors of the economy.

By the use of θ_g, the influence of an investment in the public sector upon national capital accumulation during the initial investment and construction phase is taken into account.

2. <u>Social value of net additional income received by sectors of the economy</u>. The social value of net additional income received

by sector i and the portions of it that are consumed and reinvested are taken into consideration by:

$$V_{ity} = [(1-\mu_i)\eta_i](1-P_i)b_{ity} + \frac{\rho_i}{r}[1-(1-\mu_i)\eta_i](1-P_i)b_{ity} \qquad (2.7)$$

in which V_{ity} = social value of net additional income received by sector i at period t at a scale of development y.

μ_i = average propensity to save in sector i.

η_i = income elasticity of demand for consumption goods, in sector i (change in the amount of goods consumed produced by a change in the consumer's income).

b_{ity} = benefit, before payment to government for products or services received from project to sector i at period t when scale of development is y.

P_i = percent of b_{ity} paid to government by sector i for products and services (assumed constant over time and independent of scale of development).

The first term of the right-hand side represents the value of additional consumption, and the second term of the right-hand side represents the social value of reinvestment in the sector.

3. Revenue received from the operation of the project. Because the productivity of capital in various sectors, the social rate of discount, and the social rate of opportunity cost of capital in the government sector are not equal, the revenue received by the public sector from the operation of the project is included in the economic evaluation:

$$G_{ty} = \sum_{i=1}^{n} P_i \, b_{ity} - O_{ty} \qquad (2.8)$$

in which G_{ty} = net government revenue at time t and scale of development y

O_{ty} = operational, maintenance, and replacement (OMR) cost of project at time t.

Each dollar of this net revenue has a social value θ_g.

4. Opportunity costs of productive factors. Because opportunity costs of productive factors are not correctly measured by market prices due to the already mentioned imperfections of the market in developing countries, a distortion produced by the use of market values must be avoided. So, shadow prices are used instead. Shadow prices are "the value of the marginal productivity of factors when a selection of technique has been made which produces the maximum possible volume of output, given the availability of resources, the pattern of final demand and the technological possibilities of production" (6). The use of shadow prices is restricted in this model to two key factors: the use of underemployed labor and the rate of foreign exchange.

   a. Shadow wage rate for underemployed agricultural labor. The social cost of employing unskilled underemployed labor for water resources projects is not zero. To estimate cost two types should be considered (6): Labor type A, which is removed from its own village (causing transfer and settling costs; requiring costs for food collection and redistribution; and requiring higher wages than the average farm income to induce them to move), and labor type B, which is used close to their village (requiring only transportation costs and wages higher than the marginal farm income, which

is lower than the average farm income). It is assumed that once the construction work ends, this labor will be reabsorbed by the local irrigated agricultural economy, which has higher labor requirements than dry farming agriculture. The estimation of this shadow wage rate also starts with a Cobb-Douglas type production function:

$$X_{ag} = A_{ag} L_{ag}^{\alpha_{ag}} K_{ag}^{\beta_{ag}} e^{\varepsilon_{ag} t} \tag{2.9}$$

in which X_{ag} = annual gross value of agricultural production

L_{ag} = labor requirements in agricultural sector

K_{ag} = capital invested in agriculture, including land value.

By maximizing profit in the agricultural sector and by the use of this equation, Mobasheri (6) deduces the shadow price as

$$SL = \theta_g \left[J_1 \frac{L_{ag}}{L'_{ag}} + J_2 \right] W_{co} - (2\mu_{ag} - \mu^2_{ag}) \left[J_1 \frac{L_{ag}}{L'_{ag}} W_{co} \right]^{\rho_{ag}} \frac{}{r} \tag{2.10}$$

in which SL = shadow price for unskilled underemployed agricultural laborer

$J_1 = W^*_{ag}/W_{co}$

W^*_{ag} = annual income per laborer in agriculture

$$W^*_{ag} = (h\, \rho_{ag}\, K_{ag}/L_{ag}) + W_{ag} \tag{2.11}$$

h = percent of capital invested in agriculture received by farmers

W_{ag} = wage rate for agricultural laborer

W_{co} = wage rate for unskilled construction laborer

L'_{ag} = total labor force available in agriculture

$$(L'_{ag} > L_{ag})$$

μ_{ag} = average propensity to save in the agricultura sector

J_2 = added cost due to scarce living facilities, as a ratio to W_{co} .

The assumption is made that the only taxes in the agricultural sector are excise taxes (i.e., no taxes for profit or wages), and that the income elasticity of demand for consumption goods is

$$\eta_{ag} = 1 - \mu_{ag} \tag{2.12}$$

b. <u>Shadow rate of foreign exchange</u>. The shadow rate of foreign exchange SF can be estimated in several ways (6):

When there are a few main exports, divide the incremental production cost per ton of one of these (in monetary units of the country) by the amount, in dollars, that the country can receive by exporting one ton of this commodity. Black market rates can be used as a ceiling, since they are usually higher than government controlled rates.

The objective function is then:

$$\text{Max } Z = \left[\sum_{t=1}^{T} \left\{ \sum_{i=1}^{n} [(1-\mu_i)\eta_i](1-P_i)b_{ity} + \sum_{i=1}^{n} \frac{\rho_i}{r} x \right.\right.$$

$$\left.\left. x \quad [1-(1-\mu_i)\eta_i](1-P_i)b_{ity} \right\} \left(\frac{1}{1+r} \right)^t \right] +$$

$$+ \left[\sum_{t=1}^{T} \theta_g \left[\sum_{i=1}^{n} P_i \, b_{ity} - O_{ty} \right] \left(\frac{1}{1+r} \right)^t \right] - \left[\theta_g (1-\ell_y) C_y + \right.$$

$$\left. + \left(\frac{SL}{W_{co}} \right)(\ell_y C_y) \right] + \left[\left(\frac{SF}{SG} - 1 \right) \Delta BP_y \right] \qquad (2.13)$$

in which Z = present net value of economic benefit

y = scale of development

T = economic life of project

C_y = total construction cost

ℓ_y = percent of total cost for wages of unskilled underemployed agricultural labor

GF = government foreign exchange rate

ΔBP_y = present value of net effect of the project on balance of payments when GF is used to convert foreign exchange expenditures and incomes into local currency.

(All other terms are as previously defined)

The <u>first term</u> on the right-hand side represents the social value of additional consumption and of reinvestment from all sectors during the operation phase of the project.

The <u>second term</u> represents the social value of revenues received from the operation of the project. Both are discounted to a common point in time (the beginning of the operation).

The <u>third term</u> represents the social cost of the project, and the <u>last term</u> represents the effect of the project upon the balance of payments.

ΔBP_y is computed as:

$$\Delta BP_y = -f_{cy}C_y - \sum_{t=1}^{T} f_{oty}\, O_{ty} \left(\frac{1}{1+r}\right)^t + \sum_{t=1}^{T}\left[\sum_{i=1}^{n} f_{ity}\, b_{ity}\right]\left(\frac{1}{1+r}\right)^t$$

$$- \sum_{t=1}^{T}\left[\sum_{i=1}^{n} f'_{ity}\, O_{ity}\right]\left(\frac{1}{1+r}\right)^t \qquad (2.14)$$

in which C_y = total construction and installation cost of project at scale y.

f_{cy} = percent of C_y which requires foreign exchange.

O_{ty} = OMR costs at period t.

f_{oty} = percent of O_{ty} which requires foreign exchange.

b_{ity} = benefit from project to sector i at period t and scale y.

f_{ity} = percent of b_{ity} which goes to export or to reduction of imports.

O_{ity} = associated operation cost by sector i to produce benefit b_{ity} at period t, and scale y.

f'_{ity} = percent of O_{ity} which requires foreign exchange.

If the stream of the costs and benefits to be discounted is constant and finite, Eq. (2.13) can be expressed as

$$\text{Max } Z = \left\{\sum_{i=1}^{n} [(1-\mu_i)n_i](1-P_i)b_{ity} + \sum_{i=1}^{n} \frac{\rho_i}{r}[1-(1-\mu_i)n_i](1-P_i)b_{ity}\right\} F +$$

$$+ \left\{ \theta_g \left[\sum_{i=1}^{n} P_i \, b_{ity} - O_{ty} \right] \right\} F - \left[\theta_g (1-\ell_y) C_y + \left(\frac{SL}{W_{co}}\right) (\ell_y C_y) \right] +$$

$$+ \left[\left(\frac{SF}{SG} - 1\right) \Delta BP_y \right] \tag{2.15}$$

and Equation (2.14) as

$$\Delta BP_y = f_{cy} \, C_y - f_{oty} \, O_{ty} \, F + \left[\sum_{i=1}^{n} f_{ity} \, b_{ity} \right] F - \left[\sum_{i=1}^{n} f'_{ity} \, O_{ity} \right] F \tag{2.16}$$

in which the factor $F = \dfrac{(1+r)^T - 1}{r(1+r)^t} = \dfrac{1-(1+r)^{-T}}{r}$ (2.17)

is the present value of an annuity.

In water-resources projects the annual benefits start gradually and do not reach the estimated values until a few years have elapsed. In some instances, such as in the case of irrigation charges, a government in a developing country may give the water free of charge for the first few years of a new project, in order to help the farmers to get started. In these cases a factor similar to F can be used (6):

1. If it is assumed that the return is increasing uniformly during the initial years of the project:

$$F' = \left[\frac{1-(1+r)^{-T}}{r} - \frac{1-(1+r)^{-t}}{r} \right] + \left[\frac{1}{t} + \frac{1}{t} \left(\frac{1}{r} - \frac{t}{(1+r)^t - 1} \right) \right] \left[\frac{1-(1+r)^{-t}}{r} \right] \tag{2.18}$$

in which t = period during which the return increases uniformly.

T = economic life of project.

2. If no return is obtained during the first t years of the T years of economic life:

$$F'' = \frac{1-(1+r)^{-T}}{r} - \frac{1-(1+r)^{-t}}{r} \tag{2.19}$$

Autoregressive Processes

The topic of parameter estimation for autoregressive processes is first reviewed in a general manner, leading to the particular case of first-order processes and the sampling properties of their parameter.

Autoregressive Processes: If a pure random process, i.e., a process whose autocovariance function vanishes for all lags not equal to zero, is an input to a linear system, the output is defined as an autoregressive process (23). In discrete time the relationship between input η_t and output ε_t in a linear system can be described by the solution to a linear difference equation. For a first-order linear system it can be shown (23) that this relationship reduces to

$$\varepsilon_t = \phi_1 \varepsilon_{t-1} + \eta_t \tag{2.20}$$

which is the first-order autoregressive or Markov model.

Parameter Estimation: Box and Jenkins (24) discuss the manner in which exact maximum likelihood estimates of the parameters of an autoregressive process can be obtained. Because the resultant equations are complicated functions of these parameters, four approximations have been suggested (23), (24):

1. Exact least squares estimates.
2. Approximate maximum-likelihood estimates.

3. Yule-Walker estimates (also approximate maximum likelihood estimates).

4. Least-squares estimates of the regression coefficients of a regression whose "dependent" variable is ε_t and whose "independent" variables are ε_{t-1}, ε_{t-2}, etc.

In the case of a first-order autoregressive model, the Yule-Walker estimates are approximations to the parameter ϕ_1 by means of the first-order autocorrelation coefficient r_1 (24). Several ways to estimate r_1 are found in the literature (25)(26).

When both the "dependent" and "independent" variables are random variables, all estimates of the parameter ϕ_1 are biased (27)(28). This bias depends upon the population value of the parameter and upon the sample size (26). Several ways have been suggested to obtain approximately unbiased estimates of r_1 (25), (26), (28), (29). These corrections, however, will depend on which estimate of r_1 is being used, which is not always explicitly stated in the literature.

Supply

Traditionally, the design of a water-resources facility--such as a reservoir for conservation purposes--has been based on an analysis of the historic streamflow sequence available at the proposed site. From this historic sequence, a "critical period" (or period during which the least favorable streamflow conditions existed for the purpose of the design) was selected and, on this basis, the required reservoir size was obtained by a mass curve analysis. Because of the stochastic nature of streamflows, there is no assurance that the observed streamflow sequence will repeat itself in the future. There are many sequences, all equally likely, that can occur. Within these sequences, one or

several periods which are more "critical" than the historic "critical period" may also occur.

Autoregressive Models: Models for stochastic generation of equally likely streamflow sequences tend to preserve certain statistical characteristics estimated from the available historic streamflow sequences. It is generally believed that, unless the historic record is very meagre, these characteristics may constitute good estimates of the population parameters. However, in the case of annual flow series between 40 to 60 years are needed to obtain estimates of the mean and variance, with errors varying from 2 to 20 percent and from 15 to 60 percent respectively. The normalized standard error of estimate for the first autocorrelation coefficient was found to be of the order of 200 percent with less than 40 years of data (30). The models most generally used for streamflow simulation are first-order Markov models. Their structure incorporates a deterministic component and a residual, which follows a first-order Markov model as in Eq. (2.20).

$$\varepsilon_t = \phi_1 \varepsilon_{t-1} + \eta_t \tag{2.20}$$

in which ε_t = residual at time t

ϕ_1 = autoregressive coefficient

ε_{t-1} = residual at time $t-1$

η_t = independent stochastic component for time t

Some of the latest ones incorporate a cylic variation into the parameters of their deterministic component, such as the mean, standard deviation, and first order autocorrelation coefficient of flows (31). Some take into account the 12 computed monthly values of these parameters (in monthly generation, for example), and some represent the parameters by

the sum of harmonics in a Fourier Series expansion. Some models use the observed flows and others use a previous tranformation, such as the logarithms of the flows.

In the work by Rodriguez et al., (31), a comparison of four types of autoregressive models was made with respect to their adequacy for simulating monthly streamflow sequences, which preserved certain properties of the historical record that were considered important for the design of reservoir storage capacity. All models had a cyclic structure and their most important characteristics are summarized in Table 2.1. Their conclusions regarding these models are as follows (31):

> The cyclic or seasonal variation in the standard deviation should be incorporated in any model to be used for studying storage characteristics. The inclusion of seasonal variations in parameters like the skewness and the first autocorrelation coefficient does not improve the overall performance of model 4.
>
> The type of distribution used for the random component of the model does not appear to have major influence in the reproduction of the historical range when the mean value of the series is used as reference level.
>
> Serious problems may arise when working with logarithmic models which tend to preserve the statistics of the logarithmic series rather than those of the historical record. The magnitude of the distortion increases when the statistics of the logarithmic series are drastically changed as a function of the increment added to the original series in order to avoid infinite logarithms for zero flows.

Broken-Line Model: Autoregressive models, although the most common are not the only ones which can be used for streamflow simulation. For example, a "broken-line" model has been studied by Ditlevsen (32) and, more recently, by Mejia, Rodriguez and Dawdy (33). These studies have shown that if the second derivative of the correlogram at the origin $\rho''(o)$ of a stationary process exists, the extreme values and

TABLE 2.1

Characteristics of the Four Streamflow Generation Models Compared in Reference (31)

Model	Periodicity Estimated by		Periodic Component Considered in				Uses Logarithms Transformation of Flows	Distribution of Random Component	Amplitudes and Phases of the Basic Cycle
	Fourier Analysis	Directly from Data	Means	Standard Deviation	Skewness Coef.	First Order Auto Correlation Coef.			
1	Yes		Yes					Normal	Constant
2	Yes		Yes	Yes				Normal	Constant
3	Yes		Yes					Normal	Time Varying
4		Yes	Yes	Yes	Yes	Yes	Yes *	Pearson III	

* In order to avoid infinite logarithms when zero values are present, a small increment is added to each monthly flow.

crossing properties of such a process are related to this parameter. Moreover, a longer "memory" can be included in the model much more easily than in autoregressive models by using fewer parameters.

Following the work by Ditlevsen (32) and Mejia et al., (33), the broken-line model can be described by Figures 2.2 and 2.3 and by the following equations.

The meaning of Figure 2.2 is that a given value of a stationary process, such as Q_t, can be obtained by a sum of points in a series of broken lines of different frequencies. This can be expressed by

$$Q(t) = \sum_{i=1}^{N} \xi_i(t) \tag{2.21}$$

in which N is the number of broken lines added. Furthermore, $\xi_i(t)$ can be expressed by

$$\xi_i(t'-k_i a_i) = \eta_{i,n} + \frac{(t'-na_i)}{a_i}(\eta_{i,n+1}-\eta_{i,n})$$

$$t' \in [na_i, (n+1)a_i] \tag{2.22}$$

in which the η_i's are mutually independent, identically distributed random variables with zero mean and variance σ_i^2, and the k_i's are uniformly distributed $[0,1]$ random variables independent of the η_i's. The parameter a_i is a given positive number or "memory parameter." The meaning of the above equation can be obtained from Figure 2.3.

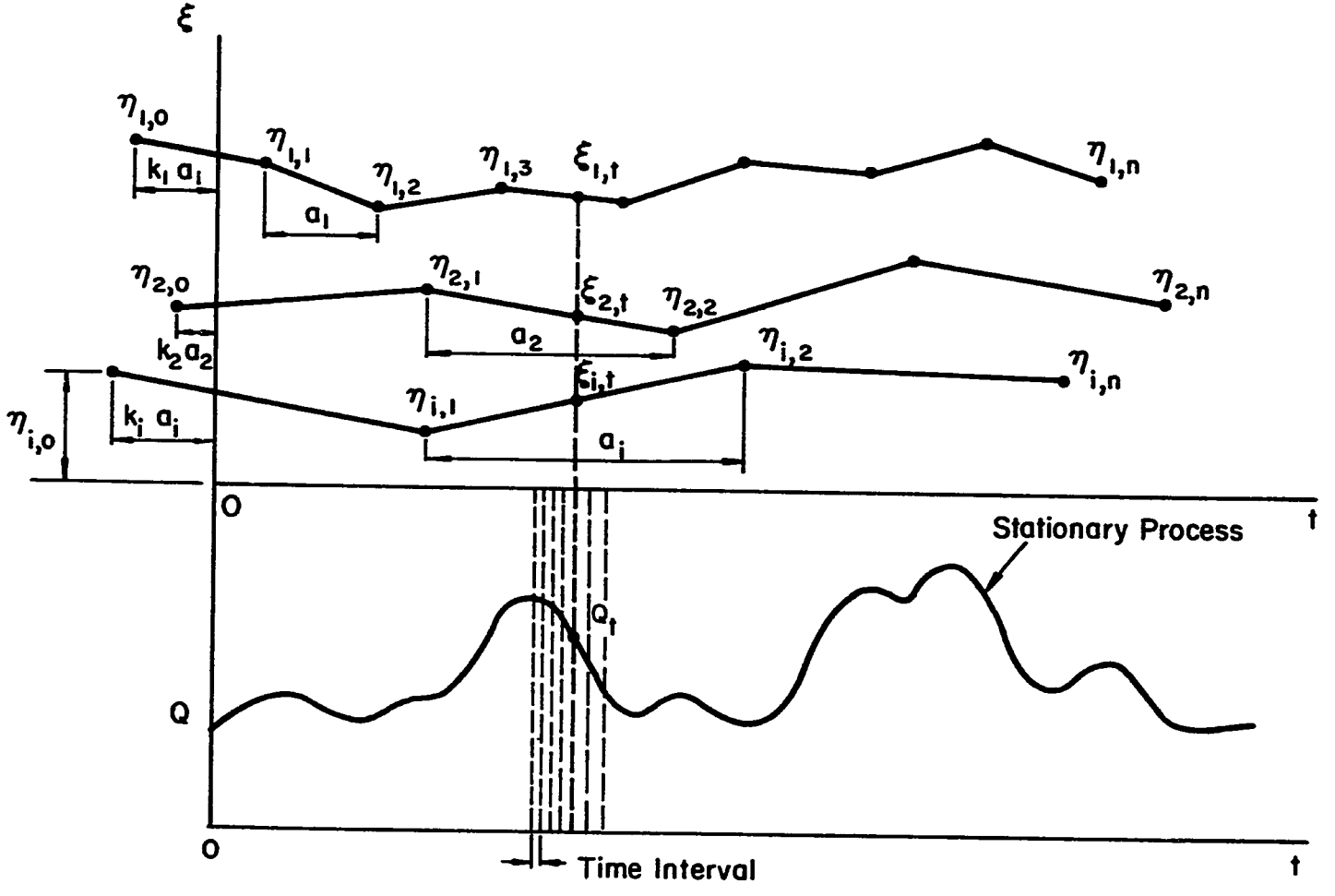

Figure 2.2. Broken-Line Model

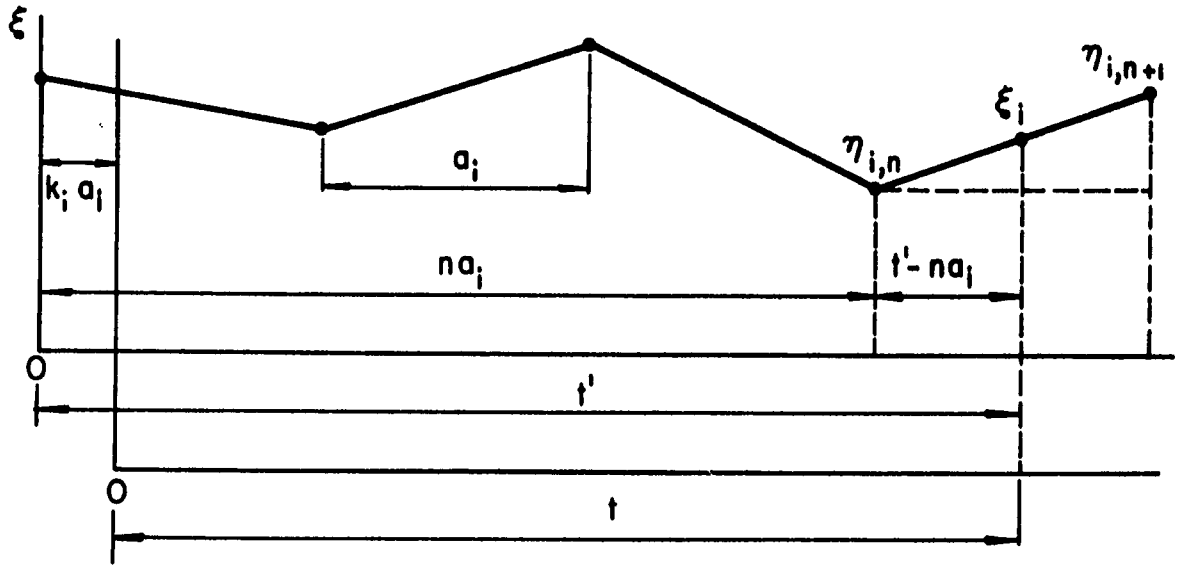

Figure 2.3. Single Broken-Line Process

The single broken line process, as described by Equation (2.22) has the following autocorrelation function:

$$\rho_i(t) = \begin{cases} 1 - \frac{3}{4}(t/a_i)^2(2 - t/a_i) & \text{for } \frac{|t|}{a_i} \in [0,1] \\ -\frac{1}{4}(t/a_i - 2)^3 & \text{for } \frac{|t|}{a_i} \in [1,2] \\ 0 & \text{for } \frac{|t|}{a_i} \in [2,\infty] \end{cases} \tag{2.23}$$

in which t is the lag. The autocorrelation function of the broken-line process given by Equation (2.21) is

$$\rho(t) = \frac{\sum_{i=1}^{N} \sigma_i^2 \rho_i(t)}{\sum_{i=1}^{N} \sigma_i^2} \tag{2.24}$$

in which $\rho_i(t)$ is given by Equation (2.23) and $\sum_{i=1}^{N} \sigma_i^2$ is obtained from

$$\frac{2}{3} \sum_{i=1}^{N} \sigma_i^2 = 1 \tag{2.25}$$

which is the variance of the process. The correlogram "dies-off" at $t = 2a_n$ and its second derivative at the origin is given by

$$\rho''(o) = -2 \sum_{i=1}^{N} \left(\frac{\sigma_i}{a_i} \right)^2 \quad . \tag{2.26}$$

The parameters of the broken line process are thus N (the number of broken lines), N memory parameters a_i, and N variances σ_i^2.

Requirements

The terms "water requirements" and "water demands" will be used interchangeably to mean those water quantities that a given water resources project is expected to deliver under certain specified conditions for allowable shortages. The three types of water demands most commonly found in developing countries are for urban supplies, for irrigation, and for hydropower generation. A deterministic approach has been traditionally used for their estimation. Lately, their stochastic nature has been recognized and studied (36), (37), (38).

Deterministic Approach: The traditional way of estimating water demands has followed a deterministic approach, i.e., to postulate a model to describe the relationship among the factors involved and, once these factors are evaluated, to assume that the model determines a certain result.

Irrigation: An estimation of the future crops and crop patterns in the project area is made, along with the area to be covered by each crop. If irrigation is going to be of a supplemental nature, an estimation of the average effective precipitation (i.e., that portion of precipitation that is available for crop-use) is made for each period considered (e.g., months). An estimation of the crop consumptive use (that quantity of water required by crops for their proper growth) for each period is then obtained. The Blaney-Criddle method for estimating consumptive use utilized by the Soil Conservation Service (34) has been adopted with some modifications in some developing countries because the data required are usually available (mean monthly temperature, monthly percentage of annual daylight hours, and an empirical crop-use coefficient). The difference between the consumptive use and the effective precipitation is the water needed by each crop which, multiplied by the area to be covered by the crop, gives the total water requirement. After a correction for irrigation efficiency and conveyeance losses is made, the quantity of water to be delivered by the project for each period is obtained.

Hydro-Power: This involves a projection of energy demands, which may be done in several ways, two of which are (22): by extrapolation of trends based on an historical record of energy consumption, and by per capita consumptions estimated in comparison with other countries. The former method may not be adequate if supply has been limited by the means of production rather than by demands, as is usually the case in developing countries. The latter method involves a projection of the growth of both population and national economy, since it is based on

estimates of future energy per capita per year and Gross National Product per capita per year. This estimated future growth of annual energy demand is met by staging the construction of projects, not all of which are hydro. If a given portion of the annual demand at a given stage is to be satisfied by a hydro project, the water requirements are estimated as follows (35):

1. From a historical record of the energy used each year and each period of the year (e.g., months) an average percentage of annual energy used in each period is determined. This percentage multiplied by the estimated future annual energy demand gives the estimated energy demands for each period.
2. The water requirements for each period are then easily estimated by the known formula

$$Q_t = \frac{E_t}{9.8 \times h \times \varepsilon \times h.p.p.} \qquad (2.27)$$

in which Q_t = flow in period t (cubic meters per second)

E_t = energy demand for period t (Kw-hours)

h = net average head (meters)

ε = estimated efficiency of turbines and generators

h.p.p. = number of hours per period

3. The portion of the annual demand to be satisfied by the hydro project is found by a succesive approximations procedure from a mass curve analysis of water supply and demand, repeating step 2 each time.
4. The ratio between a hypothetical average power demand over a given period and the maximum power required during this period

gives the load factor for that period. The average power demand for a period (in Kw) can be obtained from historical records by dividing the energy demand for the period (in Kw-hr) by the number of hours in that period. The maximum power required during a given period may also be obtained from historical records, usually given as the peak hourly demand in that period. The capacity to be installed can then be obtained as follows:

$$\text{Installed capacity in Kw} = \max\left[\frac{E_t}{\text{h.p.p. x L.F.}}\right] \qquad (2.28)$$

in which E_t = average energy demand for period t (Kw-hr)

h.p.p. = number of hours per period

L.F. = average load factor for the period

Urban Water Supply: The method of estimation of urban water supply demands is somewhat similar to that for power demands (35). It includes projections of population and of per capita consumption from which to estimate the quantity of water required for each period. As is the case for power, this also involves projections of economic conditions since these will have an influence on per capita consumption. If water for industries is included in the water supply, the estimation of future demands will be more complex. Usually, industrial demands are considered apart from urban water supplies, which include only water for what is called "municipal uses" (human and household consumption, fire-fighting, public areas, etc.).

Stochastic Approach: Projections of future conditions are subject to a great deal of uncertainty. In the first place, the demands are deterministic-stochastic time series and the future values cannot be expressed by unique values (they could if the variability introduced by

the stochastic component in them were insignificant compared to the deterministic component and if this deterministic component did not change with time). Unlike supply sequences, it has not been so widely recognized, however, that the demands or water requirements on which the designs are based may also be stochastic in nature and either dependent or independent of the streamflow or supply sequences (36). In fact, although many references can be found in the literature on which the stochastic nature of the streamflow is accounted for, only two (37) (38) were found in the present review of the literature in which a definite attempt to treat the demands as stochastic variables has been reported.

Irrigation: In reference (38) the use of stochastic irrigation demand sequences is reported by taking into account the stochastic nature of both precipitation and evaporation. As stated before, this was the only reference found which studied this aspect.

Urban Water Supply: In the case of urban water supplies, an analysis such as the one presented at the Urban Water Resources Systems Institute recently held at Colorado State University (39) shows that three components may be identified from a historical series of water demands: a trend, a cyclic component, and a stochastic component. However, the existence or absence of water meters, the pricing system and the composition of the population served, are factors which complicate the analysis and comparison of historical water demand series. Furthermore, even if a trend is identified it will change with time, so that a projection of this trend into the future (which is usually based on population projections) is subject to uncertainty. Similar considerations can be made for power demands, although the picture is here complicated

by the fact that historical records of power demands in developing countries are restricted, in the sense that supply has been limited by the means of production. Altouney in his dissertation (7) makes an excellent review and analysis of the different methods of population projection. He also analyzes a total of 128 separate forecasts of the national population of the United States, and 405 forecasts (generally made by the arithmetic, geometric or graphical method) made by local engineers for cities or metropolitan areas, concluding that for national projections no systematic bias existed (a cycle of underestimation generally followed a cycle of overestimation) but that for local projections, engineers tended to overestimate (the "safety factor"). He also concluded that the length of the forecast period appeared to be more significant for the accuracy of the results than the projection method used. He presents curves showing the variation of the average m and standard deviation s of the ratios of actual to predicted population on a national and local level, with the forecast period in years. Statistical tests indicated that the ratios of actual to estimated future local population followed a normal distribution.

Hydro-Power: Monte Carlo techniques* were used in reference (37) to generate annual power demands. A triangular probability density function was assumed for the annual demand growth rate. The parameters defining this function were a pessimistic, an optimistic, and a "most probable" growth rate estimate for each year, with the additional condition that the area enclosed by the triangle equalled unity.

---

* Procedures by which a series of random numbers following a given probability distribution is obtained.

The Objective Function

Every uncertainty involves an additional cost that must be added to those included in a situation where all the consequences of a decision are assumed to be known accurately in advance. Several procedures to explicitly take uncertainty into account in decision making were reviewed by Dorfman (40). The concept of a "loss function" was proposed to make some allowance for the uncertainty introduced by the stochastic nature of the hydrology, by using the expected value of the loss function. This loss function is viewed as a measure of the loss due to the difference in benefits obtained as a result of the actual sequence of streamflows, and those that would have been obtained if the quantity of the water for which the project was designed would have been available. The form proposed by Dorfman and used extensively throughout reference (40) is as follows:

$$Z(Y_n, Y_t) = B(Y_n) - L(Y_n - Y_t) \tag{2.29}$$

in which Z = expected net benefits in period t, as a function of Y_n and Y_t.

Y_n = normal supply of water for which the project was designed.

Y_t = supply of water actually obtained in period t

B = normal net benefits that would have been obtained in period t if the supply during that period would have been Y_n.

L = expected value of the losses due to the fact that the supply was Y_t and not Y_n; as a function of $Y_n - Y_t$.

This same procedure was used by Hufschmidt and Fiering in their simulation model of the Lehigh River Basin in Pennsylvania (14), although they suggested the maximization of a function

$$Z = \mu + R\sigma \tag{2.30}$$

in which μ is the present value of expected net benefits; σ is the present value of the standard deviation of net benefits; and R (a negative value) is a parameter of risk aversion. Because the economic impact of a deficit is more important than that of an excess (since water users are usually set up to work with a given assured quantity of water and sometimes cannot use any available excess) more emphasis has been given to the losses, although it is recognized that "negative losses" can also occur.

The concept of a loss function has been subsequently used and modified by several authors. Fiering (41) presented a general type of loss function which incorporates the effect of the sequence of the shortages, i.e., whether they occur consecutively or spaced in time. This loss function is of the following type:

$$L = \sum_{t=1}^{T} \ell_t \tag{2.31}$$

$$\ell_t = \left(\sum_{i=1}^{p} b_{i,t}\, \delta_i^k \right) N_t^{\alpha}$$

in which L = total loss in all T periods considered.

ℓ_t = loss in period t.

$b_{i,t}$ = input coefficient (for example the relationship between an economic loss and a water shortage).

δ_i = flow requirement minus outflow in subperiod i (positive or otherwise zero).

N_t = number of consecutive shortages in period t.

P = number of subperiods i in each period t .

T = total number of periods t considered.

k, α = input coefficients

The "shortage index" concept presented by Beard (42) falls within this general framework. This shortage index is defined as the sum of the squares of annual shortage ratios over a 100-year period. A shortage ratio is the difference between the quantity of water required and supplied, divided by the quantity demanded. This ratio, computed for each year, is squared and added over the period considered. This sum is divided by the number of years in the period and multiplied by 100 to convert it to a 100 year period. The shortage index is then

$$I = \left(\sum_{t=1}^{T} S_t^2 \right) \frac{100}{T} \tag{2.32}$$

in which:

S_t (a positive value, zero otherwise) = shortage ratio for year t =

$$S_t = \frac{Y_{n,t} - Y_t}{Y_{n,t}} \tag{2.33}$$

$Y_{n,t}$ = demand for year t .

Y_t = supply for year t .

T = number of years considered

An economic measure of the losses can be obtained if this index is multiplied by an appropriate coefficient "K" , which can be a function of the present value of an average annual economic unit loss "b" as will be shown later. The same result can be obtained by making $p = 1$, $k = 2$, $\alpha = 0$, and b a constant in Equation (2.31).

Relative Importance of the Planning Data

So far, as reported by James, Bower, and Matalas (43) "only a few limited efforts to assess the relative importance of the planning variables have been made." Among these efforts the work by Altouney (7) can be considered as one of the most important initial contributions in this respect. He proposed a way to evaluate a-posteriori the probability that a given estimated net benefit is equalled or exceeded, based on the estimated costs and population projections. He did not, however, consider the demands or the hydrology as periodic-stochastic time series, and he did not treat the problem of design to maximize the net benefits in accordance with a given probability of being equalled or exceeded. Nevertheless, his work showed the importance of the uncertainties introduced in the designs by the cost and benefit estimations. The effect of the streamflow record length was studied by Dawdy, Kubik and Close (44). They showed that in water resources project design, the expected net benefits decreased as the length of hydrologic record decreased, thus suggesting a way to estimate the "worth" of a given increment of record length. Their results also showed that the variability of the required storage capacity increased as the record length decreased. This was corroborated in the study reported by Close, Beard, and Dawdy (45) in which they showed that the variance of net benefits increased as the length of streamflow record decreased.

The work of James et al., however, is perhaps the most complete to date. They considered a series of reservoirs designed to meet water supply and estuarine water quality requirements downstream. They tested the sensitivity of the system performance--measured by the number of

months of failure to meet dissolved oxygen requirements (D.O.)--to two alternative values of four variables: the waste load and water-supply projection for year 2010 based on population projections (economic), the dissolved oxygen target (political), the modeling of estuarial behavior (physical), and the length of the sequence of monthly streamflows (hydrologic). By an analysis of variance, they found that portion of the total variance of the number of monthly failures of D.O., that could be atttributed to each of the four variables and ranked them accordingly (economic, political, physical, and hydrologic). They treated only a component of the demand (the projection of the trend), and they were not concerned with the design to maximize net economic benefits.

Young, Orlob, and Roesner (13) pointed out that the net economic benefits could be considered as a function F of independent random variables, contained in two vectors of economic data E and of hydrologic parameters H . The approximate general expression for the variance of net benefits was:

$$\text{var}\ (B) = \sum_{i=1}^{n} \left(\frac{\partial F}{\partial e_i}\right)^2 \text{var}\ (e_i) + \sum_{j=1}^{m} \left(\frac{\partial F}{\partial h_j}\right) \text{var}\ (h_j) \qquad (2.34)$$

in which:

e_i = an element of E

h_j = an element of H

This implies that the variance of net benefits depends not only upon the variance of each economic and hydrologic element but also upon the response of the optimization model to unit changes in these elements. The efforts should then be directed towards reducing the variance (if

feasible) of those elements with respect to which the partial derivatives of F were the largest.

CHAPTER III

EXAMPLE PROJECT

A real case in a developing country was selected to set the stage for this research. Real situations were considered, real data were used, and real data limitations were confronted. This line was followed as long as possible, although certain departures from it were necessary.

The project selected is located in Guatemala, Central America. Existing studies on it are at a very preliminary stage, so that it practically had to be developed "from scratch" based on the available information. A detailed description of its location, water uses, geophysical and economic data analysis, demand projections, cost and benefit estimation, benefit-cost analysis, and determination of the coefficients needed by Mobasheri's model is included in the Appendix. Only a brief summary of its location and description and the results of the conventional benefit-cost analysis is included in this chapter. The sources of information for this chapter are those listed alphabetically at the end of the Appendix.

Location

The government of Guatemala is considering the development of land and water resources in an area of about 14,400 square kilometers located in the northern part of the country, lying within 90°30' longitude West, and 15°00' and 16°00' latitude North. Except for its East-central part, this region is underdeveloped and very few settlements exist within it. There is also a colonization project for the region north of the 15°40' parallel, lying between the 91°15' meridian at the West and the Caribbean Sea at the East. This project (see Figure 3.1) includes the building of roads and other infrastructure

features and is aimed at decreasing the demographic pressure now existi in the Western highlands. Preliminary studies show good possibilities for hydro-power generation and for the obtaining of water for municipal and agricultural purposes by means of a series of dams and reservoirs located at several places along the main rivers within the project area. One of these sites could be El Jocote, on the Chixoy River (drainage area approximately 5762 square kilometers). The site at El Jocote is located at approximately 37 kilometers Southwest of Cobán, the provincial capital of Alta Verapaz, and at approximately 90 kilometers North of Guatemala City, the nucleus of the central power district. Some 50 kilometers to the North of El Jocote, the existence of approximately 42,800 Hectares of land with moderate suitability for irrigation has been estimated.

Water Uses

From topographic maps it was determined that physical conditions would allow the building of a dam with a maximum height of 240 meters (elevation 560 to 800 meters) and a maximum crest length of about 840 meters in a V-shaped canyon. The only road relocation would be that of about 10 kilometers of the old road from Huehuetenango to Cobán. An additional 180 meters of fixed head could be obtained by a tunnel of 9.75 kilometers. Thus, by assuming a minimum reservoir head of 50 meters, 230 meters of fixed head would be available. Since the mean annual flow of Chixoy River at that point is about 66 cubic meters per second there are good possibilities for hydro-power development. From El Jocote, releases for irrigation could be made to the Chixoy River (through the turbines whenever possible) and diverted at a point

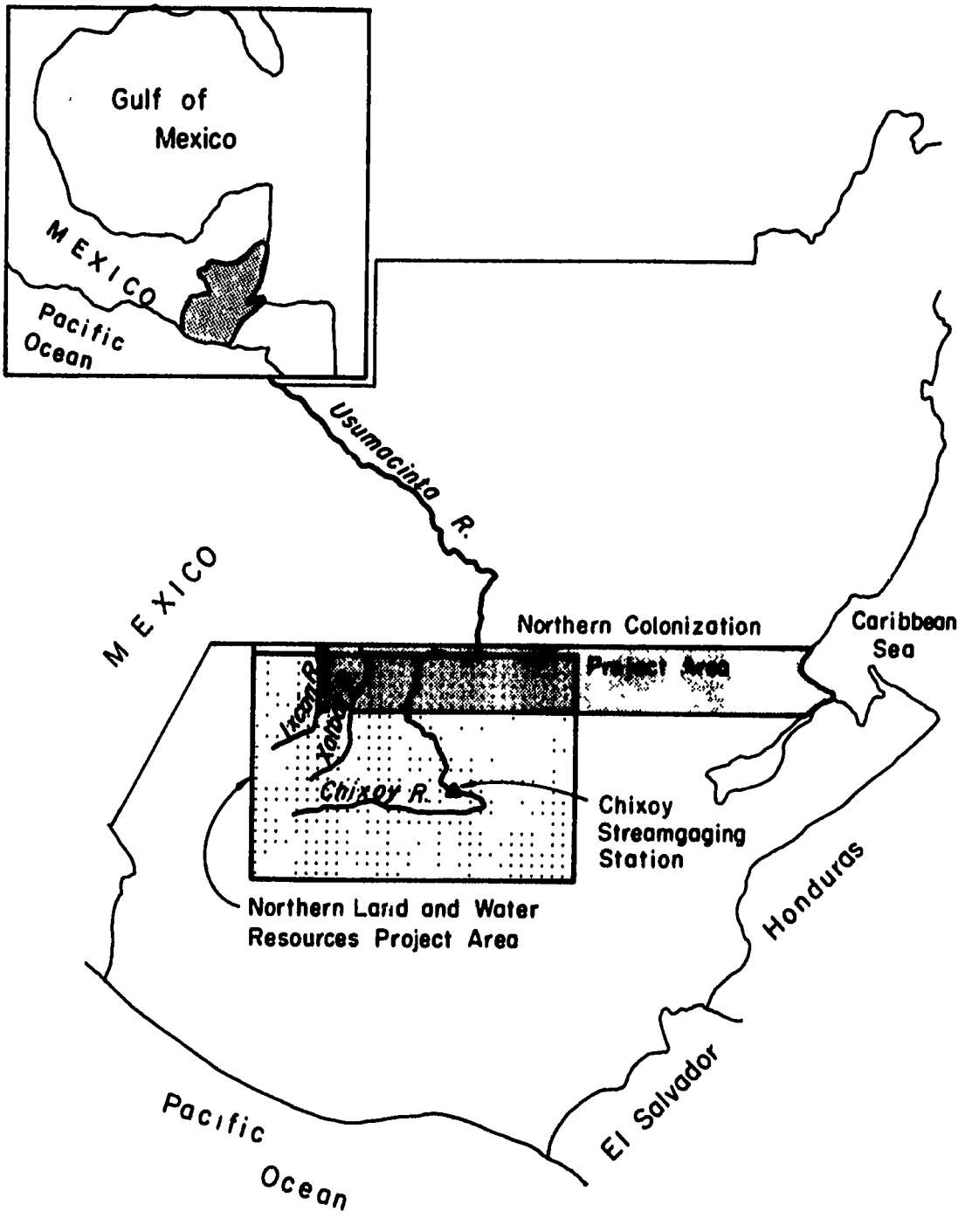

Figure 3.1

Location Map for the Guatemala Project

some 40 kilometers downstream. From this point water would be conveyed to the irrigation areas by lined conveyance canals.

The system layout is as follows:

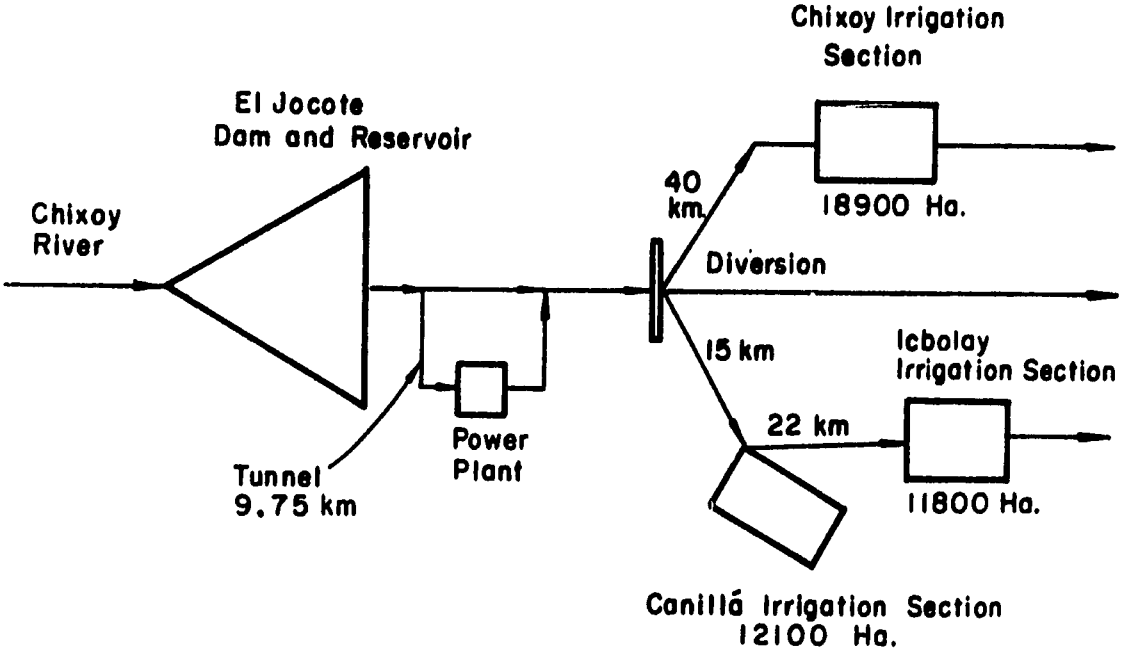

Figure 3.2. System Layout of the Example Project.

Benefit-Cost Analysis

This section is divided into sub-sections about cost, benefits, and net benefits.

Costs: The computation of costs was based on the sizes of the different elements of the project and on the cost curves given in the Appendix*. A summary of these costs is as follows:

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* Costs and benefits are given in Quetzales, the monetary unit of Guatemala, represented by the symbol Q . The equivalence is 1 Q = 1 U.S. $.

Element Sizes:

Reservoir:	1060 $X10^6$ cubic meters
Hydro plant:	175,000 Kw
Irrigated area:	24,700 Ha (including 2,000 Ha involving pumping)
Conveyance canals:	55 Km
Tunnels	9.75 Km
Transmission lines:	37 Km
Diversion works:	L = 250 m ; h = 25 m

Capital Costs:

Reservoir	Q 58,000,000
Hydro plant	30,000,000
Tunnel	12,550,000
Transmission	1,180,000
Diversion	5,450,000
Conveyance	9,620,000
Irrigation network	6,800,000
Pumps	400,000
	Q 124,000,000

Annual Costs:

Power plant	Q 750,000
Reservoir	38,000
Irrigation	240,000
Pumping	12,000
	Q 1,040,000

Benefits: Benefits from irrigation are obtained from Figure A.9 of the Appendix. Energy prices in Guatemala are structured as follows:

$$TV = NI + OE \tag{3.1}$$

in which TV is the total energy value, NI is the net income of the power entity, and OE is its operation expenses. These operation expenses include direct expenses, depreciation, administration expenses, general expenses, and operation and maintenance costs. The net income is given by

$$NI = \frac{re}{100} \times FC \tag{3.2}$$

in which re is the rentability rate of the power entity in percent, and FC is the fixed capital. The fixed capital includes the investment in both construction and operation of the different components of the system. The total energy value becomes then

$$TV = \left(\frac{re}{100} \right) FC + OE \tag{3.3}$$

According to the national development plan, the total investment planned up to 1979 is Q 137,934,400 including all previous investments but excluding this project. According to plans, the total available energy for 1980 will be 1,557.75 million kw-h. Total operation expenses were not given, but they were estimated based on historical data of operation expenses and installed energy and from estimates made for some of the projects planned for the decade of the seventies . A figure of Q 14,000,000 was obtained.

To convert the total energy value to a price per kw-h TV , as given by Equation (3.3), was divided by 85 percent of the 1,557.75 million kw-h estimated for 1979 (15 percent losses are assumed for transmission and distribution). The energy price adding El Jocote Project would be computed as follows:

$$EP = \frac{\frac{re}{100}(137\ 934\ 100 + \Delta FC) + (14x10^6 + \Delta OE)}{(1\ 557\ 750\ 000 \times 0.85 + 0.85\ \Delta E)} \qquad (3.4)$$

in which EP is the energy price in Q/kw-h , ΔFC is the investment to be made in this project, ΔOE is the operation expenses of this project, and ΔE is the annual energy to be produced by this project. For an re of 9 percent, this price is Q 0.018/kw-h.

Net Benefits: Based on the above, and using the "traditional procedure" described in Chapter II, Table 3.1 shows, for different discount rates, the stream of costs and benefits during an estimated economic life of 50 years. From this table, it is seen that the internal rate of return of the whole project lies between 11 and 12 percent (closer to 12 percent).

TABLE 3.1

Benefit-Cost Analysis for El Jocote Project, Assuming an Energy Price of Q 0.018/kw-h and a Net Rentability for the Power Entity of 9 Percent.

Discount Rate in Percent r	Actualization Factor $\frac{(1+r)^T - 1}{r(1+r)^T}$	Costs in Million Q			Benefits (Present Value) in Million Q	Net Benefits (Present Value) in Million Q
		Capital	O and M (Present Value)	Total		
6	15.76	124.00	16.40	140.40	246.00	105.60
7	13.80	124.00	14.40	138.40	216.00	77.60
8	12.23	124.00	12.80	136.80	192.00	55.20
9	11.00	124.00	11.45	135.45	172.00	36.55
10	9.90	124.00	10.30	134.30	155.00	20.70
11	9.02	124.00	9.40	133.40	141.00	7.60
12	8.30	124.00	8.65	132.65	132.00	-0.65

CHAPTER IV

DETERMINISTIC MODEL

To obtain a preliminary estimate of the "optimum" value of the design variables, as stated in Chapter I, a discontinuous deterministic model is used.

Setting of the Model

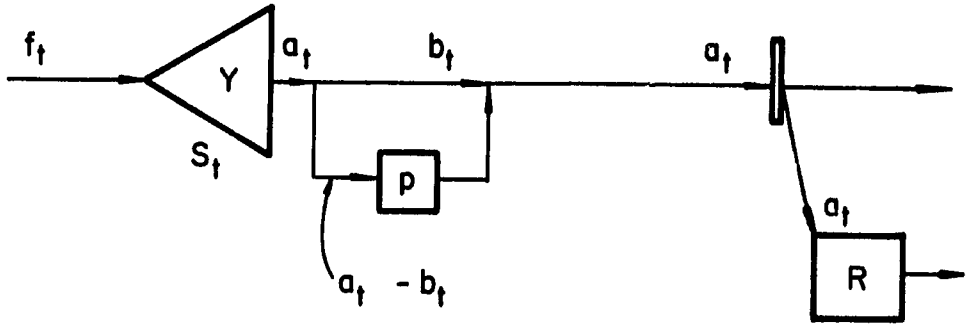
For the supply and demands, each year of a "critical period" was divided into two six-month periods: a wet period from May to October, and a dry period from November to April. Average values for each period were used. The "critical period" was assumed to be the five years for which storage capacity was required according to a mass diagram analysis.

The objective was to determine that combination of irrigated land area, installed capacity of the power plant, and reservoir storage required to maximize the objective function subject to certain constraints, as specified in the next section. For the evaluation of the present value of net benefits, the economic model proposed by Mobasheri (6) was used (see Chapter II). It was assumed that the benefits to industry and agriculture, as well as the net revenue from energy sales, increase uniformly during the first five years of operation of the project, to reach their constant value at the end of the fifth year, and that the farmers receive the water free of charge during the first five years in order to help them get established. The coefficients of Equations (2.15) and (2.16) were evaluated based on the parameter values assigned in Section A.5 of the Appendix.

Three crops were originally considered: Pasture, corn, and beans; part of the area for beans included some pumping. However, preliminary trials showed that the coefficients in the objective function of the variables corresponding to the areas with pumping were negative, so they were eliminated from the analysis. Moreover, the deterministic demands for irrigation resulting from the analysis were of minor importance when compared with the deterministic demands for power. Since this could impair the sensitivity analysis to be done afterwards in relation to the effect of the correlation among supply and demand sequences, a hypothetical crop was considered. This hypothetical crop was assumed to have twice the irrigated requirements of beans, the same seasonal distribution of these requirements and the same benefits per irrigated hectare. The total available land for this hypothetical crop was assumed to be 80,000 hectares, at a distance of 15 Kms. from the diversion. This land is less than the upper limit considered by Maass et al., (40) to be feasible for irrigation without pumping, but is about twice the amount considered available in the region. As far as irrigation is concerned then, the example departs from reality. However, a departure, from reality already was made when for the sake of the research effort, irrigation was kept within the analysis although the preliminary conventional economic evaluation suggested it be eliminated. In that instance, however, a political decision might have produced the same effect whereas no political decision can increase the irrigation demands and/or increase the land available for irrigation.

Table 4.1 gives the data used for the deterministic model and Figure 4.1 shows the revised system layout.

Figure 4.1. System Description for the Deterministic Model



f_t = flow in period t in 10^6 cubic meters, $t = 1,2,\ldots,10$.

Y = storage reservoir size including minimum pool, in 10^6 cubic meters.

S_t = contents of reservoir at the beginning of period t , in 10^6 cubic meters.

a_t = total releases from reservoir during period t , in 10^6 cubic meters.

b_t = portion of the reservoir releases not used for power generation during period t , in 10^6 cubic meters.

P = installed capacity of power plant in 10^6 kw.

$$P = \text{Max}\left(\frac{C_t E}{L.F._t \times \text{hours in 6 months}}\right) = 0.000194E$$

E = annual energy demand to be satisfied by project, in 10^6 kw-h.

R = area to be irrigated, in 10^6 Ha.

TABLE 4.1

Data Used in the Deterministic Model*

Year	Streamflow in Million Cubic Meters f_t		Irrigation Requirements in Cubic Meters per Hectare. r_t		Average Load Factor $L.F._t$		Seasonal Average Percentage of Annual Energy C_t	
	Wet Season	Dry Season	Wet Season	Dry Season	Wet Season	Dry Season	Wet Season	Dry Season
1962-63	1,100	384	0	12,600	0.6103	0.5849	0.5024	0.4976
1963-64	892	390	0	12,600	0.6103	0.5849	0.5024	0.4976
1964-65	1,101	400	0	12,600	0.6103	0.5849	0.5024	0.4976
1965-66	1,060	502	0	12,600	0.6103	0.5849	0.5024	0.4976
1966-67	1,835	496	0	12,600	0.6103	0.5849	0.5024	0.4976

* Obtained from sources listed in section A.7 of the Appendix.

Description of the Model

The description of the model is divided into two parts: The description of the objective function, and the description of the constraints.

Objective Function: Equations (2.15) and (2.16) can be combined into an expression of the following type:

$$\text{Max. } Z = \sum_{i=1}^{n} C_{i,x} X_i \tag{4.1}$$

in which Z = present value of net benefits.

$C_{i,x}$ = a coefficient (which can be positive or negative and not necessarily constant) including present value of annuity factors, the net effect of costs and benefits corresponding to a scale of development x of variable i, net effects on balance of payments, shadow rates for underemployed labor, social capital productivity rate, etc.

x_i = variable i developed to scale x.

n = number of variables.

Equation (4.1) can be nonlinear or linear depending on whether the coefficients $C_{i,x}$ do or do not include one or more of the variables X_i in their structure.

Combining Equations (4.1) and (3.4) and using the data of section A.5 of the Appendix, the objective function of the deterministic model is as follows:

$$\begin{aligned} \text{Max } Z = {} & (19.20B_R - 24.11O_R - 1.2145C_R)R - (0.00444O_p + 0.000243C_p)E \\ & + \left[0.277 + 8.60 \left\{ \frac{\frac{re}{100}[(151.6644) + (0.000194E)C_p + C_y Y] + [14.0 + (0.000194E)O_p + O_y Y]}{[1320 + 0.85E]} \right\}\right] E \\ & - (22.8O_y + 1.234C_y)Y - (0.2159)L - 23.766 \end{aligned} \tag{4.2}$$

in which:

Z = present value of net benefits, in Q 10^6.

R = area to be irrigated, in 10^6 Ha.

E = annual energy demand to be satisfied, in 10^6 kw-h.

Y = storage reservoir size including minimum pool, in 10^6 cubic meters.

B_R, O_R, and C_R = annual benefits, annual operation and maintenance costs, and capital costs for irrigation, in Q 10^6 per 10^6 Ha.

O_p and C_p = annual operation and maintenance costs, and capital costs for the power plant, in Q 10^6 per 10^6 Kw.

O_y and C_y = annual operation and maintenance costs, and capital costs for the storage reservoir, in Q 10^6 per 10^6 cubic meters.

re = net rentability for power in percent.

L = length of conveyance canal, in Kms.

By defining $Z' = Z + (.215900)L + 23.766$ and maximizing Z' the last two terms of Equation (4.2) are eliminated. The value of L is 15 Kms. if irrigation is included and zero otherwise. All the costs and benefits in this equation are nonlinear functions of the elements R, P, and Y, so this equation is actually nonlinear of an order higher than two.

<u>Constraints</u>: The following groups of constraints were considered:

1. The area to be irrigated cannot be greater than the total available area:

$$R \leq 0.08 \tag{4.3}$$

2. The contents of the reservoir at the beginning of period t, must not exceed the contents of the reservoir at the beginning

of period t-1 plus the inflow during period t-1 minus the outflow during period t-1 :

$$a_{t-1}-S_{t-1}+S_t \leq f_{t-1} \tag{4.4}$$

3. The total releases from the reservoir during period t should not be less than the irrigation requirements for that period. If r_t is the requirement for period t in 10^6 cubic meters per 10^6 Hectares, this can be expressed as follows:

$$a_t-r_tR \geq 0 \tag{4.5}$$

4. The contents of the reservoir at the beginning of period t plus the inflow during the period minus the outflow during the period should not exceed the conservation capacity of the reservoir. Since the minimum pool is 108 $X10^6$ cubic meters, this constraint can be written as follows:

$$a_t-S_t+Y \geq f_t+108 \tag{4.6}$$

5. The releases during any period should not be less than those necessary to produce the energy for each period. The water volume requirements to produce a given quantity of energy during any period, can be evaluated using Equation (2.27). Calling $\overline{H}$ the average gross head in meters and using the efficiencies assumed for Table A.6 of the Appendix, this constraint is as follows:

$$a_t-b_t-\frac{480\ E_t}{\overline{H}} \geq 0 \tag{4.7}$$

However, Figure A.5 of the Appendix shows that $\overline{H} = 230 + \overline{H}'$, and $\overline{H}'$ is a nonlinear function of the average conservation storage volume.

6. The energy produced during each period should not be less than the specified percentage of the annual energy for that period:

$$\frac{1}{C_t} E_t - E \geq 0 \tag{4.8}$$

7. The energy price cannot exceed Q 0.018 per Kw-h

$$\frac{\frac{re}{100}\,[151.6644+(0.000194E)C_p+C_yY]+[14.0+(0.000194E)O_p+O_yY]}{1320+0.85\ E} \leq 0.018 \tag{4.9}$$

8. The net power rentability cannot be less than 9 percent:

$$re \geq 9 \tag{4.10}$$

In addition, all the variables R , E , Y , E_t , a_t , b_t , S_t , and re must be nonnegative. Constraints Equations (4.4) and (4.6) assure that the content of the reservoir at the beginning of each period is not greater than the reservoir capacity and that the reservoir capacity is greater than or equal to the minimum pool.

Solution

The objective is to find the values of the variables R , E , Y , E_t , a_t , b_t , S_t , and re that maximize the objective function (Equation 4.2) subject to the constraints of Equations (4.3) to (4.10). Equation (4.2) as well as the constraints Equations (4.7) and (4.9) are nonlinear. Three approaches for solution were considered:

1. Use of a nonlinear optimization procedure.
2. "Linearize" the curved surfaces determined by the objective function and by the nonlinear constraints by passing planes through three points at a time (equivalent to a piece-wise linearization of a function of one variable).
3. Make simplifying assumptions that would allow the problem to be re-stated as an ordinary linear programming problem.

Since the nonlinearities are to be considered in the final solution by simulation, when the stochastic nature of both supply and demand are also to be included, a nonlinear optimization for this preliminary screening was not considered a necessity. The piece-wise linearization increased the size and complexity of the original problem and proved to be inefficient. A closer look at Equations (4.2) to (4.10) revealed that great simplifications could be obtained by making assumptions whose effect could in part be counteracted by successive approximations involving a relatively few number of trials. These assumptions are:

1. The unitary costs for the different elements and the unitary benefits from irrigation are constant.
2. The average head in the reservoir is constant.
3. The price of energy is constant and equal to Q 0.018/kw-h.

If the sensitivity of an optimal basic solution of a linear programming problem is not too great with respect to changes in the coefficients of the objective function, very few trials need to be made, adjusting the unitary benefits and costs each time, to arrive at an approximate maximum. The procedure does not proceed as blindly as it

may appear, since a ranging analysis* of the unitary costs and benefits will aid in determining whether another trial is needed or if the optimal value of the objective function can be computed from its value at the previous trial and the value of the variables at the previous trial. The average head in the reservoir is not constant, but the minimum head is large in relation to the variability of head (see Fig. A.5 of the Appendix), so that it is not unreasonable to expect the sensitivity of the solution to the variable portion to be small. The third assumption, plus the assumption that the net rentability is a constant, may convert the problem to a linear programming case without loss of significance, as will be seen.

The assumption is made that the planning agency wants the energy price not to be greater than Q 0.018/kw-h and the power net rentability not to be less than 9 percent (see constraints Equations (4.9)(4.10)). Keeping the assumption of a 9 percent power rentability, and an energy price of Q 0.02/kw-h for "without project" conditions (see Table A.7 and section A.5 of the Appendix), the following procedure can be applied:

1. Assume the price to be 0.018/kw-h and, eliminating constraints Equations (4.9) and (4.10), find the optimizing values of E and Y, say $E^{\checkmark}$ and $Y^{\checkmark}$.

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* This analysis will give the range of the coefficients for which the optimal basic solution to the linear programming problem will remain unchanged. Some linear programming computer subroutines include this analysis as an optional output. A more complete treatment of ranging and other types of sensetivity analysis can be found in the books by Wagner (47) and by Hillier and Lieberman (1).

2. With $E^{\checkmark}$ and $Y^{\checkmark}$ and the assumed energy price, re can be found from Equation (4.9) used as an equality.
3. If re > 9 percent, the price could be lowered if desired to give $\frac{re}{100} = 0.09$ or it could be maintained at Q 0.018/kw-h to give the higher re .
4. If re < 9 percent, the price would have to be raised to give $\frac{re}{100} = 0.09$ with the given $E^{\checkmark}$ and $Y^{\checkmark}$, so that constraint Equation (4.9) would be active and $E^{\checkmark}$ and $Y^{\checkmark}$ would have to be re-computed including that constraint in the analysis if it is desired to keep the price at or below Q 0.018/kw-h.

Based on the above considerations, the deterministic model used was a linear programming model (the adoption of such a model for the preliminary screening has additional attraction, as stated in Chapter I) which can be described as follows:

$$\left.\begin{array}{ll} & \text{Max } Z' = C'_R R + 0.432E - C'_p E - C'_y Y \\ \text{subject to:} & R \leq 0.08 \\ & \left.\begin{array}{l} a_{t-1} - S_{t-1} + S_t \leq f_{t-1} \\ a_t - r_t R \geq 0 \\ a_t - S_t + Y \geq f_t + 108 \\ a_t - b_t - \frac{480}{\bar{H}} E_t \geq 0 \\ \frac{1}{C_t} F_t \geq 0 \end{array}\right\} t=1,2,\ldots 10 \end{array}\right\} \quad (4.11)$$

in which:

$$C'_R = 19.2\ B_R - 24.11\ O_R - 1.2145\ C_R$$

$$C'_p = 0.00444\ O_p + 0.000243\ C_p \qquad (4.12)$$

$$C'_y = 22.8\ O_y + 1.234\ C_y$$

A first trial was made assuming $P = 0.155\ X10^6$ kw($E = 800\ X10^6$ kw-h) , $Y = 1060\ X10^6$ cubic meters, and $R = 0.04\ X10^6$ Ha for unitary costs and benefits, and $\overline{H} = 283$ m ; obtaining optimum values of $E^{\checkmark} = 919\ X10^6$ kw-h , $Y^{\checkmark} = 846\ X10^6$ cubic meters and $R^{\checkmark} = 0.062\ X10^6$ Ha . A second trial was made changing the $\overline{H}$ to correspond to $Y = 846\ X10^6$ cubic meters, obtaining $E^{\checkmark} = 910.79\ X10^6$ kw-h , $Y^{\checkmark} = 846\ X10^6$ cubic meters and $R^{\checkmark} = 0.062\ X10^6$ Ha . The value of R was changed to recompute irrigation unitary costs and benefits for a third trial, giving the same values for $E^{\checkmark}$, $Y^{\checkmark}$, and $R^{\checkmark}$ of trial two. A ranging analysis of the coefficients C'_R , C'_p , and C'_y obtained as an output from the linear programming algorithm used, showed that $E^{\checkmark}$, $Y^{\checkmark}$ and $R^{\checkmark}$ would not change if a new trial were made recomputing the unitary costs and benefits for new values $E = E^{\checkmark}$, $Y = Y^{\checkmark}$, and $R = R^{\checkmark}$, and by assuming and $\overline{H}$ corresponding to $Y^{\checkmark}$. The change in the maximum value of Z' was computed using the expression

$$Z^{\checkmark 1}_{final} = Z^{\checkmark 1}_{trial\ 3} + (R^{\checkmark}\Delta C'_R + E^{\checkmark}\Delta C'_p + Y^{\checkmark}\Delta C'_y) \qquad (4.13)$$

The final solution was:

$$Z^{\checkmark 1} = Q\ 284,114,823$$

$$Z^{\checkmark} = Q\ 257,118,823 \text{ (net social benefits)}$$

$E^{\checkmark} = 910.79 \times 10^6$ kw-h ($p^{\checkmark}$ 177,000 kw)

$R^{\checkmark} = 62{,}000$ Ha

$Y^{\checkmark} = 846 \times 10^6$ cubic meters

The solution also indicated that unless there is excess water, all releases should be made through the turbines, and that no more energy than the specified percentage of the annual energy should be generated during each period (as should have been expected since no benefit was assigned to surpluses). From Equation (4.9) as an equality and the above values of the elements of the system, the value of re is approximately 10 percent if the energy price is maintained at Q 0.018/kw-h, thus complying with constraints Equations (4.9) and (4.10). It is worth mentioning that, although the coefficient C'_R in Equation (4.11) was positive for all trials (and so R was kept in the solution) the constant conveyance and diversion costs, which add up to Q 8,075,000, are enough to cancel the positive net benefits from irrigation resulting from this positive coefficient. Nevertheless, irrigation was kept because of the reasons given in section A 4.2 of the Appendix and earlier in this chapter.

CHAPTER V

STOCHASTIC SUPPLY AND DEMAND SEQUENCES

A review of what is currently being done with regard to the inclusion of the stochastic nature of supply and demand sequences was made in Chapter II. This chapter picks up the subject where it was left in Chapter II and elaborates on it. The procedures finally chosen to be used for the stochastic model in Chapter VI and the reasons supporting these choices are given.

Supply

Because of the results obtained by Rodriguez et al., (31) presented in Chapter II, a model like model 2 discussed there was deemed adequate to simulate streamflow sequences. This model is conceptually as follows:

Series = cyclicity in the mean + cyclicity in the standard deviation, times the random component.

It can be represented by

$$x_{p,\tau} = \mu_\tau + \sigma_\tau \varepsilon_t \qquad \left.\begin{array}{l} \tau = 1,2,\ldots,\omega \\ p = 1,2,\ldots,n \\ t = 1,2,\ldots,n\omega \end{array}\right\} \qquad (5.1)$$

in which:

$x_{p,\tau}$ = flow at period τ of year p.

μ_τ = periodic component in the mean.

σ_τ = periodic component in the standard deviation.

ε_t = random component.

ω = basic period of the series.

n = number of ω periods in the series.

The models most generally used for streamflow simulation assume that the random component ε_t follows a first-order Markov model as given by Equation (2.20). Many tests (48) have given support to this assumption. There may be cases, however, where this assumption fails and where even higher-order autoregressive processes cannot adequately describe the autocorrelation structure of streamflows. In those cases models other than Markovian should be tried.

In the model adopted, the inclusion of cyclicity for the autoregressive coefficient was not considered to improve the overall performance of the model (after Rodriguez et al., (31)). Therefore, the number of data available for estimation (if monthly series are considered) is 12 times that which would be available if cyclicity were considered. Thus 96 values can be used from eight years of record, for example, instead of only eight values, increasing the reliability of the estimates of this coefficient. The importance of this will become apparent later in the section on autoregressive models, where the problems in the estimation of this coefficient are discussed.

Cyclic Components: Two alternatives were considered for the incorporation of the cyclic variation of the mean and standard deviation:

1. By the sum of harmonics in a Fourier Series expansion, where μ_τ and σ_τ of Equation (5.1) are computed as shown in Table 5.1.

TABLE 5.1

Equations for the Computation of μ_τ and σ_τ of Equation 5.1 by the Sum of Harmonics in a Fourier Series Expansion (36).

$$\mu_\tau = \mu_m + \sum_{j=1}^{m} \left(A_j \cos \frac{2\pi j}{\omega} \tau + B_j \sin \frac{2\pi j}{\omega} \tau\right)$$

$$A_j = \frac{2}{\omega} \sum_{\tau=1}^{\omega} (\mu_\tau - \mu_m) \cos \frac{2\pi j}{\omega} \tau$$

$$B_j = \frac{2}{\omega} \sum_{\tau=1}^{\omega} (\mu_\tau - \mu_m) \sin \frac{2\pi j}{\omega} \tau$$

in which:

μ_τ = periodic component in the mean

μ_m = mean of the μ_τ series

ω = basic period of the series

m = number of significant harmonics

$\tau = 1,2,\ldots,\omega$

and

$$\sigma_\tau = \mu_s + \sum_{j=1}^{m} \left(A_j' \cos \frac{2\pi j}{\omega} \tau + B_j' \sin \frac{2\pi j}{\omega} \tau\right)$$

$$A_j' = \frac{2}{\omega} \sum_{\tau=1}^{\omega} (\sigma_\tau - \mu_s) \cos \frac{2\pi j}{\omega} \tau$$

$$B_j' = \frac{2}{\omega} \sum_{\tau=1}^{\omega} (\sigma_\tau - \mu_s) \sin \frac{2\pi j}{\omega} \tau$$

in which

σ_τ = periodic component in the standard deviation

μ_s = mean of the σ_τ series.

2. By using the 12 monthly means and standard deviations as computed from the historical record.

With four significant harmonics for both the mean and standard deviation of the Chixoy River flows (8 years), it was found that the serial (or auto) correlation structure of the residuals ε_t (see Equation (5.1)) was not preserved. The first serial correlation coefficient of the ε's was estimated as 0.623 when using the 12 monthly means and standard deviations computed from the historical record, but it became -0.010 (0 for practical purposes) when these means and standard deviations were fitted by the Fourier Series model. The reason for this can be seen in Table 5.2 and Figure 5.1. In order to fit the high values of the means by the sum of harmonics, the required amplitudes and phases introduce an oscillation in the region of the lower values of this parameter. The mean of a given month is lower than the historical, so that the residual computed as $\varepsilon_t = (x_{p,\tau}-\mu_\tau)/\sigma_\tau$ will generally be positive. For the next month the situation is reversed. The lower months have the greatest influence in the determination of the autocorrelation of the series, so that the historical first-order autocorrelation coefficient was not preserved.

It is also evident that the sum of harmonics model does not preserve the sample mean nor the sample standard deviation. The selection of the model thus depends upon a question of objectives. It would be desirable to simulate streamflow sequences whose means, standard deviations and correlation structure resemble those of the population. But the population parameters are not known, so estimates are obtained through the available sample. Since the statistics of the available

TABLE 5.2

Monthly Means for the Chixoy River Computed From the Historical Record (1962-63 to 1969-70) and Fitted by a Sum of Harmonics

Month	Mean Flow in Cubic Meters/Second	
	Computed	Fitted
May	23.025	26.710
Jun	99.250	97.676
Jul	101.738	101.489
Aug	86.538	87.830
Sep	154.012	152.732
Oct	146.800	147.013
Nov	55.975	57.601
Dec	37.125	33.388
Jan	26.312	31.872
Feb	23.075	16.472
Mar	19.538	26.128
Apr	19.675	14.153

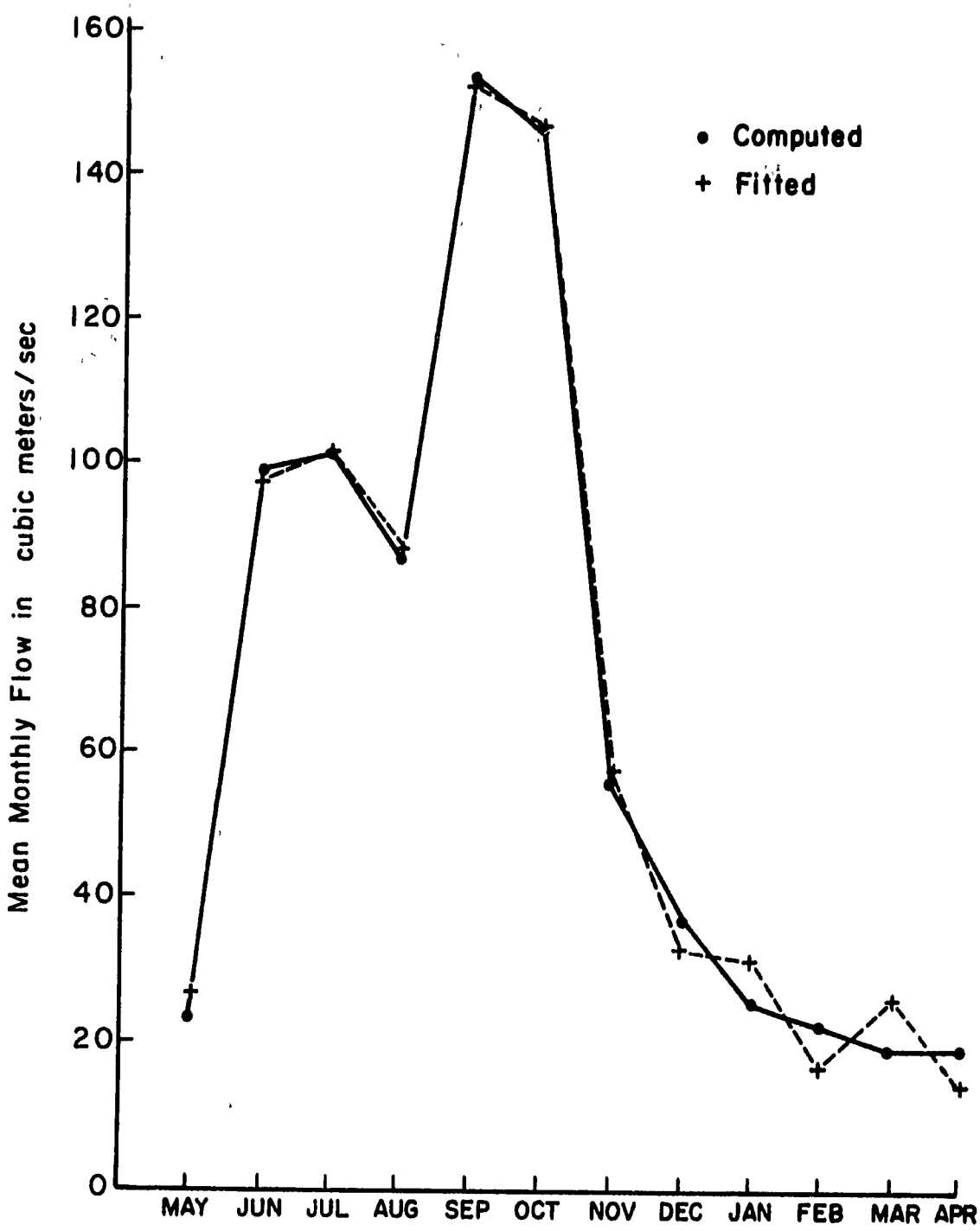

Figure 5.1

Monthly Means for the Chixoy River Computed from the Historical Record (1962-63 to 1969-70) and Fitted by a Sum of Harmonics

sample are the only estimates at hand, the objective becomes to simulate sequences whose statistics resemble those of the sample.

The bias involved is a fact of life. But from this point on, the argument becomes philosophical in nature. For example, the monthly means and standard deviations could be estimated with acceptable errors from the historical streamflow records of from 40 to 60 years (as reviewed in Chapter II), so that in such cases there is a point in trying to preserve the sample means and standard deviations (they are the only estimates and are not so bad...). The first-order autocorrelation coefficient is a different story. The estimate that can be obtained from the sample is very unreliable. It has a high estimation error even for 40 to 60 years of record (see Chapter II) and it has an estimation bias which does not become negligible unless sample sizes are of the order of from 250-1000 (see section on autoregressive models later in this chapter).

Why then try to preserve the sample value? And if the sample size is of the order of 5, 8, or 10 years (which is the rule rather than the exception in most developing countries), why try also to preserve the means and standard deviations? Such are the pitfalls of stochastic streamflow simulation. However, as stated in Chapter I, efforts are being made to obtain generalized statistics through regional analyses, which can be considered more reliable estimates of the population parameters than those obtained from a single short record. Regionalized values of means may not be so difficult to obtain, but the difficulty may be expected to increase when statistics such as the standard deviation or serial correlation coefficients are concerned. Because of this,

the relative influence of these statistics on the economic measure of project desirability is investigated in Chapter VII.

Returning to the discussion of the choice of the model to account for the cyclicity, the question reduces to a desirability of the preservation of the sample statistics. If there are no other estimates of the population parameters, it seems that the only alternative is to preserve the historical values, unless by some other means it were known that certain values different from the historical should be preserved in the generated sequences. Since in the present case there is no other alternative, a model that uses the historical sample means and standard deviations was selected.

Stochastic Component: Two alternatives were considered for the simulation of the stochastic component: by an autoregressive model, and by a broken-line model.

Autoregressive Models: The issue of the stochastic component, is not so innocent as it might appear; not even after reducing the problem to the estimation of its autocorrelation structure. This is shown in Table 5.3.

In Table 5.3, the r_k's were computed using the open series approach (36), the confidence limits for r_k were computed using Anderson's formula as given in reference (36), and the regression coefficients were obtained from a step-wise multiple regression analysis using an existing computer program package (49). This table shows two important features:

1. The correlogram stays way above the confidence limits.
2. A peculiar dependence with lags 1, 4, 6, and 8 is evident.

TABLE 5.3

Autocorrelation and Autoregression Coefficients for the Residuals $\varepsilon_t = (x_{p,\tau}-\mu_\tau)/\sigma_\tau$ of Chixoy River Monthly Flows

Lag k (months)	1	2	3	4	5	6	7	8	9	10
Autocorrelation Coeff. r_k	0.623	0.496	0.464	0.531	0.456	0.530	0.513	0.549	0.347	0.411
95 Percent Confidence Limits for r_k	0.157	0.158	0.159	0.160	0.161	0.161	0.162	0.163	0.164	0.165
	-0.178	-0.179	-0.180	-0.181	-0.182	-0.184	-0.185	-0.186	-0.187	-0.188
Autoregression Coeff. ϕ_k	0.399	(NS)*	(NS)	0.178	(NS)	0.227	(NS)	0.272	-0.252	0.122

* NS is entered for "not significant", meaning that its inclusion in the regression equation will not make any significant reduction in the error sum of squares because its F ratio is too small (49).

The first thought that comes to mind is that this peculiar behavior could be due to sampling variations, since the sample was relatively small (96 values). Moreover, if a first-order autoregressive model $\varepsilon_t = \phi_1\varepsilon_{t-1}+\eta_t$ is assumed for the ε's , the ordinates of the correlogram of the residuals η_t for lags one to ten are: -0.105, 0.015, 0.018, 0.261, -0.042, 0.207, 0.079, 0.341, -0.170, and 0.172. For the same 95 percent confidence limits shown in Table 5.3, it is seen that only lags 4, 6, 8, and 10 are still significant. However, as the lags 1 to 3 are not significant and the correlogram now oscillates between positive and negative values, this significance can easily be misinterpreted as being caused by sampling error. One may thus be tempted to offhand dismiss this significance and assume a first-order model. However, this behavior may be caused by the characteristic karst conditions which prevail in certain parts of the watershed (see section A.1 of the Appendix). The examination of Table 5.4 which shows the correlogram of the Current River near Van Buren, Mo. (which also drains a karstic region) makes it a reasonable assumption, since 468 values (39 years) were available for this latter case.

If a first-order Markov model is assumed for the Chixoy River under the "sampling error" premise and the long dependence is really caused by the karst conditions, a type II error will be involved (i.e., accepting a hypothesis as true when it is not). If on the other hand, the hypothesis of a long dependence caused by the karst conditions is accepted and this effect is in fact caused by sampling errors, a type II error will likewise be made. The question that arises is: Which error will have the greatest effect upon the "maximum" present value of net benefits? The long dependence will probably require a larger

TABLE 5.4

Autocorrelation Coefficients for the Residuals $\varepsilon_t = (x_{p,\tau} - \mu_\tau)/\sigma_\tau$ of the Current River Monthly Flows

Lag k (months	1	2	3	4	5	6	7	8	9	10
Autocorrelation Coeff. r_k	0.469	0.315	0.325	0.321	0.202	0.180	0.115	0.131	0.091	0.126
95 Percent Confidence Limits for r_k	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.075	0.075
	-0.078	-0.078	-0.078	-0.078	-0.079	-0.079	-0.079	-0.079	-0.079	-0.079

reservoir than the Markov model, but which effect is the most important one, the over-designing of the reservoir or the shortages that might be produced by the smaller one? These questions are discussed in Chapter VII. If a first-order Markov model is assumed, the problem of the estimation of the parameter ϕ_1 (see Equation (2.20)) remains, and a discussion of some of the problems involved in the estimation of this parameter is necessary.

Several ways to estimate ϕ_1 of Equation (2.20) were reviewed as stated in Chapter II. All these estimates are biased, and this bias depends upon the sample size n and upon the population value of the parameter ϕ_1. Since there is no consensus among hydrologists as to which estimate of ϕ_1 to use, a test was performed in order to have a comparison among the most widely used forms of estimation of this parameter, and in order to have a better idea as to how these estimators introduce bias in relation to the values of ϕ_1 and n. Using the computer, several first-order Markov series with a given population parameter ϕ_1 were generated and different methods were used to obtain estimates $\hat{\phi}_1$ based on the generated series.

It was found that a downwards bias persisted for values of n up to approximately 250 in the case of $\phi_1 = 0.3$, and up to about 1,000 in the case of $\phi_1 = 0.5$ and $\phi_1 = 0.7$. It was also found that the most convenient way to estimate ϕ_1 is by an equation of the type

$$\hat{\phi}_1 = \frac{\sum_{t=2}^{n} \varepsilon_t \varepsilon_{t-1}}{\left\{ \sum_{t=2}^{n} \varepsilon_t^2 \sum_{t=2}^{n} \varepsilon_{t-1}^2 \right\}^{\frac{1}{2}}} \tag{5.2}$$

since it produced the smallest variance and ranked second with respect to the smallest bias among all the estimators that were tested.

If a long dependence is assumed, the problem is not only of parameter estimation, but involves also the choice of a model to preserve this long dependence. Assuming an eighth order autoregressive model $\varepsilon_t = \phi_1\varepsilon_{t-1}+\phi_4\varepsilon_{t-4}+\phi_6\varepsilon_{t-6}+\phi_8\varepsilon_{t-8}+\eta_t$ it was found that the roots of its characteristic equation* all lie outside the unit circle, an indication that if the process ε_t is stationary, it may be autoregressive. An examination of the correlogram of the residuals η_t of the assumed eighth-order autoregressive process indicated that they could be assumed to be uncorrelated because, although the lag-nine and a few other higher order autocorrelation coefficients were significant, the correlogram oscillated between positive and negative values.

This type of test, however, proved to be inconclusive in the case of an assumed first-order model and so the doubt persists as to what the order of the autoregressive model should be. In the present case, for example, it is conceivable that the inclusion of lag 2, or 3, or 5, or 9, or all the first 10 lags, or just the first four lags might also produce similar results. Moreover, even if the roots of the characteristic equation of the model $\varepsilon_t = \phi_1\varepsilon_{t-1}+\phi_4\varepsilon_{t-4}+\phi_6\varepsilon_{t-6}+\phi_8\varepsilon_{t-8}+\eta_t$ all fall outside the unit circle, and even if its residuals η_t could be assumed to be uncorrelated by an analysis of their correlogram, the use of the Yule-Walker equations (24) with the ϕ's from one to eight equal to 0.399, 0.0, 0.0, 0.178, 0.0, 0.277, 0.0, and 0.272, gave all

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* The characteristic equation of a kth order autoregressive process is given by $\phi(B)= 1-\phi_1B-\phi_2B^2-\ldots-\phi_kB^k=0$ where B is a backward-shift operator defined by $B^k\varepsilon_t=\varepsilon_{t-k}$ according to reference (24), pp. 8-9, 54-55.

r's greater than one. This is an indication that, even if the stepwise multiple regression analysis showed ϕ_2, ϕ_3, ϕ_5, and ϕ_7 to be non-significant, they cannot be assumed to be zero. When they were assumed to be zero, however, the test of the correlogram of residuals did not detect it.

Broken Line Model: Because all these difficulties with the autoregressive processes would impair the assesment of the type II error previously mentioned, the use of a broken-line model like the one described in Chapter II became attractive to preserve the long-persistence effect exhibited by the available sample. Because of this, it was decided to investigate the type II error between a lag-one Markovian model and a broken-line model to preserve the long-term persistence.

The broken-line model is a relatively new concept which still is in a developing stage and more research is needed in order to make it fully operational. Unlike the Markovian models, no physical meaning is attributed to it; it is rather a tool that can be used to accomplish certain purposes, like the preservation of the second derivative of the correlogram at the origin, or a given long memory. In this section, a strategy developed to simulate monthly flows with a given memory under certain conditions is described. This strategy was used in the research reported herein to preserve the long-term persistence effect exhibited by the residuals ε_t of the Chixoy River monthly flows.

The broken-line model requires the residuals ε_t to be normally distributed $N(0,1)$ (33). Since this hypothesis was rejected by a chi-square test at the 95 percent level for the residuals of the Chixoy River, they were assumed to be log-normally distributed and the

Aitchison and Brown (50) transformation was used to make them ln N(0,1) in order to preserve the means and standard deviations of the sample. Figure 5.2 shows the correlogram of these transformed residuals.

If N (the number of broken lines) were only two, the number of parameters to estimate would be four: a_1 , a_2 , σ_1^2 , and σ_2^2 . By assuming a large value for a_2 and that a_1 will be small (one long-frequency broken-line added to a short-frequency broken-line) such that $\{|t|/a_2\}\varepsilon[0,1]$ for $t = 1$ and $t = 6$, and such that $\{|t|/a_1\}\varepsilon[0,1]$ for $t = 1$ and $\varepsilon[2,\infty]$ for $t = 6$, these four parameters can be obtained by using Equations (2.23), (2.24) and (2.25) as follows:

1. From Equation (2.25):

$$\sigma_1^2 + \sigma_2^2 = 3/2 \tag{5.3}$$

2. Substituting Equation (5.3) in Equation (2.24):

$$\rho(t) = \frac{2}{3}[\sigma_1^2\rho_1(t) + \sigma_2^2\rho_2(t)] \tag{5.4}$$

3. The value of σ_2^2 can be obtained from Equation (5.4) by making $t = 6$, using the desired value for $\rho(6)$, and using Equation (2.23):

$$\rho(6) = \frac{2}{3}\{0 + \sigma_2^2[1 - \frac{3}{4}(\frac{6}{a_2})^2(2 - \frac{6}{a_2})]\} \tag{5.5}$$

4. With σ_2^2 known, σ_1^2 can be obtained directly from Equation (2.25):

$$\frac{2}{3}\sigma_1^2 + \frac{2}{3}\sigma_2^2 = 1 \tag{5.6}$$

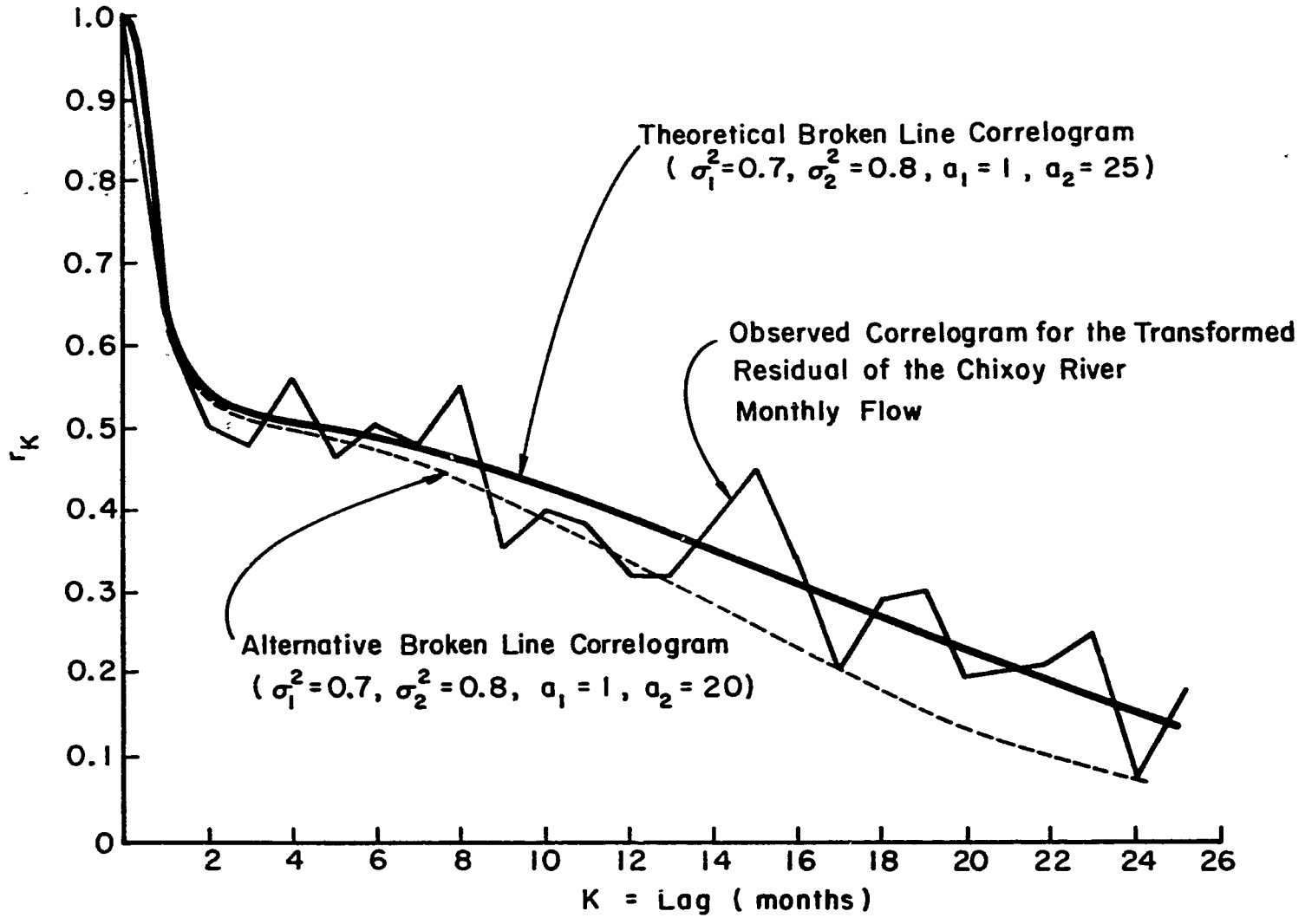

Figure 5.2. Correlograms of the Chixoy River Monthly Flows

5. With the assumed value of a_2 and the values of σ_1^2 and σ_2^2 known, the value of a_1 can be found* from Equations (5.4) and (2.23), by making $t = 1$ and using the desired value for $\rho(1)$:

$$\rho(1) = \frac{2}{3}\{\sigma_1^2[1 - \frac{3}{4}(\frac{1}{a_1})^2(2-\frac{1}{a_1})] + \sigma_2^2[1 - \frac{3}{4}(\frac{1}{a_2})^2(2-\frac{1}{a_2})]\} \quad (5.7)$$

6. If a_1 were such that $1/a_1 \varepsilon [1,2]$, the first term in the above equation should be modified in accordance with Equation (2.23).

The above procedure enables one to preserve the long memory in the residuals ε_t by generating values whose theoretical correlation structure is defined by the parameters a_1, a_2, σ_1^2, and σ_2^2. As an example, Figure 5.2 shows the observed correlogram for the residuals of the Chixoy River monthly flows, as well as the theoretical correlogram given by the broken-line process.

The problem of streamflow simulation, however, does not end with the estimation of these parameters. Due to the long memory of the process, an operational procedure is needed by which the last $2a_N$ values of the historical series are reproduced as closely as possible every time a synthetic series is generated. What this involves can be seen in Figure 2.2 and 2.3 and Equations (2.21) and (2.22): a given number of η_i's and the K_i's must be such as to generate the first $2a_N$ values as closely as possible to the last $2a_N$ values obtained from the historical record. Due to the form of Equation (2.22) this is more easily said than done. Because the time interval for monthly

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* If one would desire to preserve the value of $\rho''(0)$ instead of $\rho(1)$, Equation (2.26) should be used in this step instead of Equation (5.7).

flows is 1, if $a_1 > 1$ (a_2 surely is) more equations than $\eta_{i,n}$ unknowns may be obtained by the application of Equation (2.21). Moreover, Equation (2.22) complicates the matter by making the subscript n of the η_i's dependent upon t', which in turn is determined by the K_i's which in turn are unknowns. If $a_1 > 1$, a successive approximations least-squares procedure would have to be followed to obtain the K_i's and the η_i's.

A special case (and a very important one due to the simplifications and flexibility introduced) is when $a_1 = 1$. When this is the case, the number of $\eta_{i,n}$ unknowns may be made equal to the number of equations when Equation (2.21) is applied. The procedure is as follows:

1. By Monte-Carlo techniques, generate the K_i's as uniformly distributed $[0,1]$. By the same techniques generate the necessary $\eta_{2,n}$ as $N(0,1)$.
2. Since the time interval is equal to 1 and to a_1, the application of Equation (2.21) with the historical ε_t values substituting the Q_t's will give a number of equations in an equal number of unknowns $\eta_{1,n}$ (the value of n is fixed as soon as the K_i's are generated), from which the values of these $\eta_{1,n}$ unknown variables can be obtained directly.
3. All the rest of the $\eta_{1,n}$ and $\eta_{2,n}$ are generated by Monte-Carlo techniques, and the series is generated by Equation (2.21)
4. For each series generated, steps 1 through 3 are repeated.

The above procedure is computationally easy and it is flexible, since each series starts with a different set of K_i and η_i variables. Each generated series will reproduce exactly the last $2a_N$ historical values. It is limited, however, to cases where the observed correlogram

may be reasonably described by two broken-lines, one of long-frequency characterized by a large memory parameter a_2, and one of short frequency characterized by a memory parameter $a_1 = 1$. If the correlogram may be described by two broken lines, the limitation that a_1 must equal 1 is not too serious. The reason is that the first 10 or 12 observed autocorrelation coefficients may be reasonably approximated by making $a_1 = 1$ and changing the value of a_2 (i.e., changing the "die-off" time). Since the reliability of the autocorrelation coefficients decreases with the lag, the "die-off" time is uncertain anyway. As an example, Figure 5.2 also shows another broken-line correlogram obtained with different a_2.

Requirements

Only irrigation demands were considered as stochastic. However, a possible way of generating annual water supply demands and hydro-power demands is discussed. Water supply was not considered in the Guatemala project and the interconnection problems left stochastic hydro-power demands out of the scope of this work.

Irrigation: Because of lack of information, the assumption was made that crop yields and consumptive use could be deterministically predicted. Even so, the precipitation is a deterministic - stochastic phenomenon and the use of average values for each period may lead to erroneous conclusions. Moreover, if the land to be irrigated is within the same climatological boundaries as the watershed for the irrigation supply, then the irrigation supply and demand series may be highly correlated. If this were the case, a better design might be obtained

if these uncertainties due to the stochastic nature of supply and demand sequences were taken explicitly into consideration by simulating equally likely supply and demand series, preserving the correlation between the observed sequences. The adoption of this procedure would also allow the evaluation of the relative effect of this dependence upon the optimization.

An analysis of 14 years of monthly rainfall data for station Cubilguitz (see section A.3.1 and Table A.2 of the Appendix) showed that precipitation series could be represented by a model such as that of Equation (5.1), where the residuals ε_t are uncorrelated and follow a log-normal probability distribution function. By step-wise multiple regression analysis (49) with the residuals ε_t of the Chixoy River monthly flows, it was also found that the only significant cross correlation between rainfall and streamflow residuals was for lag-zero, which was equal to 0.24. In view of this, it was decided to generate rainfall and streamflow sequences preserving this cross correlation. The demand sequences were then obtained by using these generated rainfall sequences and the deterministic effective precipitation percentage, consumptive use requirements, and irrigation losses as used for section A.4.1 of the Appendix. Demand series with zero cross correlation with respect to streamflow were also generated to evaluate the effect of this cross correlation on the "maximum" present value of net benefits.

Water Supply: Although no water supply was considered for the Guatemala project, it is believed that stochastic simulation of annual demands could be possible based on the work by Altouney (7) reviewed in Chapter II. Knowing the distribution of the ratios of actual to estimated future local population, which Altouney showed could be

approximated by a normal distribution, several values of these ratios could be generated for a given mean m and standard deviation S by Monte Carlo techniques. This would allow one to obtain several "actual" population values based on a population prediction for a given forecast period. Repeating this procedure for succesive forecast periods, annual demands could be generated for the estimated economic life of the project.

Hydro-Power: Two possible effects of the stochastic nature of power demands were investigated: the effect on the determination of the capacity to be installed and the effect on the estimation of annual energy demands.

Installed Capacity: In the case of hydro-power, as was previously stated in Chapter II, the determination of the capacity to be installed is usually based on the estimates of energy demands for each period and on the average load factors for each period. The energy demands for each period are in turn based on an average percentage of annual energy used during each period. But the load factor and period percentage series also have a stochastic element in them, whose influence may or may not be important in relation to the deterministic component which exhibits a seasonal variation. The use of average values for each period is justified only if the deterministic component is more significant (just as it would be for streamflow series if it were not known that the stochastic component is indeed important in this case). If the stochastic component were of importance, several equally likely load factor and period percentage series could be generated by Monte Carlo methods based on the historical series.

In the present case, an analysis of the historical monthly energy percentage and the monthly load factor series showed that the variance was small, so that the use of average values for each period was considered not to introduce significant errors. The determination of the capacity to be installed was thus based on Equation (2.28).

Annual Demands: A way to generate stochastic annual energy demands was reviewed in Chapter II. These demands, however, would be placed upon the entire system and not only upon a single generation facility. The effect of stochastic annual demands on a single project, such as the one considered in this work, cannot then be taken into account unless the operation of the whole interconnected system is also considered. Since this was outside the scope of this work, annual energy demands were also included as being deterministic. It was therefore assumed that this project would satisfy an unknown percentage of the total demand and that the only concern was to estimate what capacity could be installed at that site given the topographic and streamflow characteristics.

Summary

The models finally chosen for the simulation of stochastic supply and demand series are as follows:

1. For supply, the model was that of Equation (5.1). The cyclicity in both mean and standard deviation was introduced by using the 12 historical values in each case. For the random component, two models were used: a first-order autoregressive model with an independent residual following a log-normal distribution, and a broken-line model to preserve the long

term persistence exhibited by the sample residuals of the sample flows. In the first case, Equation (5.2) was used for the first-order autoregression coefficient. Equally likely sequences were generated by using the monthly streamflow simulation model developed by Matalas (51) preserving the sample means, standard deviations, and first-order autoregression coefficient of the stochastic component of monthly flows, and the lag-zero cross correlation coefficient between the stochastic component of monthly flows and monthly precipitatio

In the second case, a broken-line model was used, following the procedures described in this chapter, to simulate equally likely streamflow sequences preserving the sample means, standard deviations, and the correlogram of the stochastic component of monthly flows with an assumed "die-off" of 50 months (see Figure 5.2). Each of the sequences generate with this model reproduced the last 50 months of the historical record, values that were discarded prior to the routing through the reservoir.

2. For demands, only irrigation was considered as stochastic. Equation (5.1) was again used as the model for rainfall simulation introducing the cyclicity by using the 12 monthly means and standard deviations as computed from the available sample. The stochastic component was serially uncorrelated. The model developed by Matalas (51) was also used to simulate rainfall sequences preserving the sample means and standard deviations as well as the lag-zero cross correlation coefficient between the stochastic component of the monthly rainfall and monthly

streamflow. The computer program used also calculated the effective rainfall and subtracted it from the required monthly consumptive use, to give the monthly simulated series in cubic meters per second of irrigation diversion requirements.

CHAPTER VI

STOCHASTIC MODEL

In this chapter the stochastic model used to obtain a better approximation to the "optimum" design and the optimization procedure selected are described and discussed. An "optimum" value for the variables is obtained following that procedure and using two streamflow generation models: a first-order autoregressive model, and a broken-line model, as stated in the summary section of Chapter V.

Final Form of the Objective Function

The main difference between the stochastic model presented in this section and the deterministic model used in Chapter IV lies in the objective function. In addition to the desirable requisites mentioned in Chapter II from an economic point of view, the objective function must also take into account the natural uncertainties caused by the stochastic nature of both supply and demand. Therefore, Equation (2.15) should be modified to accomplish this.

In the section about the objective function in Chapter II, the shortage index concept presented by Beard (42) was discussed as a form of loss function. Among the advantages of the use of a shortage index the following have been cited (44), (45), (46), (52):

1. Its computation is independent of economic values, since these may be introduced in a coefficient K, as stated at the end of the section about the objective function in Chapter II.
2. It summarizes in a single value all the shortages occurring during the economic life of a project for a given sequence

of supply and demand. This value can be used for diverse planning purposes, such as a means to determine a safety factor in reservoir design.

3. It accounts for both magnitude and frequency of shortages, since a shortage index of 0.20, for example, will represent 20 annual shortages of 10 percent each during a period of 100 years, 5 shortages of 20 percent, or 100 shortages of about 4.5 percent each during the same 100 year period.
4. At the end of the section about the objective function in Chapter II, it was stated that this index can be obtained by making $p = 1$, $k = 2$, $\alpha = 0$, and b = constant in Equation (2.31). By selecting a proper coefficient b , actual economic loss functions can usually be closely approximated by this quadratic function, since generally speaking, the consequences of a 20 percent annual shortage, for example, can be expected to be four times as severe as a 10 percent one, and so on.

The use of this shortage index, however, has some disadvantages. For example, by making $\alpha = 0$ in Equation (2.31) the effect of the timing of the shortages, i.e., whether they occur consecutively or spaced, is not taken into account. The use of a constant b also ignores whether they are expected to occur near the beginning or near the end of the expected economic life of the project. It is assumed rather than their effect is uniformly distributed along the economic life and thus, the previously mentioned coefficient K represents the present value of that average annual economic unit loss b . Beard (46)

states that "such a function,..., simply assumes that...the actual operation will be such as to minimize the effects of that shortage through forecasting and spreading the shortage over several months." This is the reason for using $\alpha = 0$ as the exponent of N_t in Equation (2.31) and also for the use of the constant b coefficient.

This assumption, however, may be no better or no worse than any other that might be made with respect to the coefficients of Equation (2.31). With respect to the duration N_t of a shortage, for example, Fiering (41) presents no criteria that may lead to the assumption that the economic loss of a shortage will increase linearly with its duration ($\alpha = 1$ in Equation (2.31)), less rapidly than linearly $(0 < \alpha < 1)$, or faster than linearly $(\alpha > 1)$. Truly, losses that occur near the end of the economic life of a project would have less economic effect than losses occurring near the beginning of it. Nevertheless, if the effect of a series of equally likely streamflow and demand sequences is being investigated, it might well be assumed that losses may occur near the end and near the beginning with similar frequency. Thus, the assumption of an "average" economic effect may not be an unreasonable one. Under these circumstances, the present value of the total loss in all T periods, considering an average squared shortage ratio for each year and starting from Equation (2.32), can be expressed as:

$$L = \theta_g \sum_{t=1}^{T} \frac{1}{(1+r)^t} b(\overline{S^2}) = \theta_g \left[\frac{(1+r)^T - 1}{r(1+r)^T}\right] b(\overline{S^2}) = \theta_g F b(\overline{S^2}) \qquad (6.1)$$

in which:

θ_g = social capital productivity rate, as defined in Chapter II.

$b(\overline{S^2})$ = annual average losses as a ratio to gross annual benefits.

r = annual interest rate.

b = annual average economic unit loss (economic loss/ shortage).

F = present value of an annuity.

Fb = present value of b.

$(\overline{S^2})$ = average of the squared shortage ratios i.e., $\sum_{t=1}^{T} S_t^2/T$, S_t as given by Equation (2.33).

Since the shortage index can be expressed as $I = 100\ (\overline{S^2})$, the present value of the total loss in all T periods is:

$$L = \theta_g \frac{FbI}{100} = KI \tag{6.2}$$

in which

K = loss coefficient = $\theta_g \frac{Fb}{100}$.

I = shortage index, as defined by Beard (42).

F and b , as previously defined.

It should be remembered that the present value of the total loss, as given by Equation (6.2), is given as a ratio to the present value of gross benefits.

The value of b can be obtained by fitting a quadratic function of the type $\overline{y} = b(\overline{S})^2$ to actual data of annual losses (as a ratio to gross annual benefits) against average annual shortage ratios, if actual annual economic loss functions can be closely approximated by quadratic functions of the type $y_t = bS_t^2$ such as the one shown in reference (46). These are constant annual losses to be expected during the whole economic life of the project, caused by a constant average

annual shortage ratio, also to be expected during the whole economic life of the project. That is, $S_t = \overline{S}$.

Using the shortage index concept to take into account the additional cost added by the uncertainty introduced by the stochastic nature of streamflow and demand, Equation (4.1) (the general form of the deterministic objective function) can be transformed to look as follows:

$$\text{Max } Z = \sum_{i=1}^{N} (C_{i,x} X_i) - \sum_{j=1}^{Q} L_j' \tag{6.3}$$

in which:

$C_{i,x}$ and X_i are as previously defined in Chapter IV.

Q = total number of water uses considered.

$L_j' = K_j I_j'(B_j J)$ = present value of the loss caused in use j by natural uncertainties of streamflow and demand, corresponding to a given scale of development J of the project.

$B_j J$ = gross annual benefits from use j when scale of development is J .

K_j = loss coefficient for use j (as previously defined).

I_j' = a function of the shortage index I_j for use j , corresponding to a given scale of development of the project.

If the effect of several equally likely sequences of streamflow and demand is to be ascertained, an expression for I_j' can be written in the following manner by using the concept expressed in Equation (2.30):

$$I_j' = \overline{I}_j + R_s D_j \tag{6.4}$$

in which:

I_j' = a shortage index with a given probability of occurrence, for a given scale of development of the project.

$\overline{I}_j$ = the average shortage index for use j, corresponding to a given scale of development.

D_j = standard deviation of the shortage indexes for use j and a given scale of development of the project.

R_s = number of standard deviations to be chosen according to a given desired probability of occurrence.

The final form is then

$$\text{Max } Z = \sum_{i=1}^{N} C_{i,x} X_i - \sum_{j=1}^{Q} K_j(\overline{I}_j + R_s D_j)(B_j J) \tag{6.5}$$

This objective function gives the present value of net economic benefits, taking into account the main concerns of a country for economic development, the principal market imperfections existing in most developing economies, and the natural uncertainties introduced by the stochastic nature of both streamflow and demand series.

Description of the Objective Function Used

To account for the uncertainty introduced by the stochastic nature of both supply and demand series, Equation (6.5) was proposed in the previous section as a general form of the objective function. In this equation, the second term on the right-hand side measures the cost of this uncertainty. The first term on the right-hand side would be equal to the objective function for the deterministic model (as given in Equation (4.11)), except for the fact that the conversion factor from the Kilowatts of power of installed capacity to annual energy is

1/0.0002125, instead of 1/0.000194, because the year is now divided into one-month periods instead of six-month periods. Taking the above into consideration and using the data of Table A.6 and section A.3.2 of the Appendix, and using Equations (2.28) and (6.2), the objective function of Equation (6.5) is, in expanded form:

$$\left.\begin{aligned}
&\text{Max } Z' = C'_R R + 0.432E - C'_p E - C'_Y Y - L'_R - L'_p \\
&\text{in which:} \quad Z' = Z + 27.006 \text{ in million Quetzales} \\
&C'_R = 19.2\ B_R - 24.11\ O_R - 1.2145\ C_R \\
&C'_p = 0.00486\ O_p + 0.000266\ C_p \\
&C'_Y = 22.8\ O_Y + 1.234\ C_Y \\
&L'_R = K_R(\overline{I}_R + R_s D_R)(B_R R) = K_R(SI_R)(B_R R) \\
&L'_p = K_p(\overline{I}_p + R_s D_p)(0.018E) = K_p(SI_p)(0.018E)
\end{aligned}\right\} \quad (6.6)$$

Here Z, R, E, Y, B_R, O_R, C_R, O_p, C_p, O_Y, and C_Y are as defined for Equation (4.2), and $\overline{I}_R$, D_R, $\overline{I}_p$, D_p, and R_s are as defined for Equation (6.4). The other terms are defined as follows:

K_R and K_p = loss coefficient for irrigation and power

$$K_R = \frac{F_R b_R}{100} = 2.28 \quad ; \quad K_p = \frac{F_p b_p}{100} = 4.82 \quad .$$

These values of K_R and K_p were obtained by using b_R and b_p equal to 9.5 and 20 (as stated in section A.3.2 of the Appendix), and by using $F_R = F_p$ = the present social value of an annuity, computed as $F \times \theta_g = 24.1$, where F is given by Equation (2.17) for the social discount rate r given by Equation (2.1), and θ_g is given by Equation

(2.2). The present values of the total losses in all T periods for irrigation and power, L'_R and L'_p, are then:

$$\left.\begin{aligned} L'_R &= 2.28\ (SI_R)(B_R R) \\ L'_p &= 4.82\ (SI_p)(0.018E) \end{aligned}\right\} \qquad (6.7)$$

in which SI_R and SI_p can be interpreted as a shortage index (as defined by Beard (42)) with a 16 percent probability of being exceeded if R_s in Equation (6.4) is made equal to one.

Another consideration must also be made with respect to the losses. Going back to the derivation of Equation (6.1), where the losses are given as a ratio to the present value of net benefits, it was stated that the annual average losses (as a ratio to annual gross benefits) were given by $\bar{y} = b(\bar{S})^2$. For a meaningful economic interpretation of the probability statement made in the above paragraph with respect to the shortage index, it would be desirable to express this statement in terms of these annual average losses, establishing a limit for them. Suppose, for example, that the following limiting values are considered as desirable: for irrigation, that the annual average losses do not exceed 1.5 percent of the annual gross benefits, and that for power this limit is set to one percent. These limits can be transferred to the allowable shortage indexes as follows:

The annual shortages are given by:

$y_j \leq p^{\ell}_j$ = the limiting percentage of annual gross benefits of use j.

so that the present value of the shortages can be expressed in the following manner:

$$\theta_g F y_j \leq \theta_g F p\ell_j$$

and using Equation (6.2), the shortage index of Equation (6.7) is given by:

$$\theta_g F b_j \frac{SI_j}{100} \leq \theta_g F p\ell_j$$

$$K_j SI_j \leq \theta_g F p\ell_j$$

$$SI_j \leq \frac{\theta_g F p\ell_j}{K_j} \tag{6.8}$$

Using the values of $\theta_g F$, $p\ell_j$, and K_j previously given for irrigation and power, Equation (6.8) becomes:

$$SI_R \leq \frac{24.1 \times 0.015}{2.28} = 0.1585$$

$$SI_p \leq \frac{24.1 \times 0.01}{4.82} = 0.05 \tag{6.9}$$

By introducing the foregoing limits into the process, it can be said that the design of the project will be such that there is an 84 percent probability that an annual average loss will not exceed 1.5 percent of the gross annual irrigation benefits, and 1 percent of the gross annual hydropower benefits. Speaking in terms of the annual shortage ratios, the above limits for SI_R and SI_p will also mean that there is an 84 percent probability that the average annual shortages will not be in excess of 3.98 percent for irrigation and 2.24 percent for power (according to the definition given for the shortage index).

Procedure

The goal was to find the values of the variables E and Y that maximized the objective function (Equation (6.6)), i.e., that contributed the most to the planning objectives as expressed by this objective function, subject to the same groups of constraints as in Chapter IV. In this case, the value of R was taken as fixed since its inclusion results from a desire to evaluate the effect of stochastic irrigation demands rather than to optimize its value, as has been discussed in previous chapters. The procedure used has a simulation component by which the response of a given set of values for the variables E , Y , and R was evaluated, and an optimization component by which the "optimum" set of values for E and Y was obtained.

Simulation Component: A computer program developed by the U.S. Corps of Engineers (53) was used for this purpose. This program computes the shortage indices for any use given a reservoir size, the installed capacity of a power plant, and a given sequence of streamflow and of diversion demands downstream. All of the storage-space constraints of Chapter IV are automatically accounted for by this program, and the irrigation and power-requirement constraints are substituted by the computation of shortages. The program also accounts for the variable head in the reservoir and for the variable evaporation losses (the evaporation data used was that of Table A.2 of the Appendix, multiplied by a pan coefficient of 0.7). It has a fixed operation rule which consists of releasing the greatest of the minimum demands in each period.

Optimization Component: From an analysis of the different optimization procedures reviewed in Chapter 10 of reference (40) and in reference (54), it was concluded that the soundest approach (although perhaps not the most elegant one*) in this case was an incremental analysis, given that the objective function is too complicated for the use of indirect methods, that the number of variables is only two (the power plant and reservoir sizes), that they are highly interrelated and that a first approximation to their "optimum" values had been previously obtained. The incremental analysis in this case was performed by increasing the size of the power plant a given amount (1,000 Kw in this case), increasing the reservoir size by an amount that would cause an increase in costs equal to the increase in benefits produced by the power plant increase, and routing the flows and demands through the reservoir using the new sizes to evaluate the shortages and compute the value of the objective function. If the value of the objective function increased, this path was continued.

If the value of the objective function decreased, a different path was tried, which consisted in decreasing the reservoir size a given amount**, making a corresponding decrease in the power plant size (so

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* In this respect, the author fully agrees with Aron (55) when he states that "...The importance of understanding and proper use of simple methods, wherever applicable, is emphasized. All too often an obvious and simple solution to a problem is being overlooked or foregone in favor of a more sophisticated approach...", and when (referring to graphical methods) he says that "...Frequently, modern but relatively complicated mathematical techniques are applied to optimize problems which could be solved by simple methods...".

** Big enough to produce a noticeable change in cost, according to the region of the cost-function over which the analysis is being made.

that marginal costs equalled marginal benefits) and routing flows and demands to evaluate the objective function. The "optimum" was obtained when the value of the objective function did not increase any more. A decrease in both instances would mean that the "optimum" had been overshot, in which case the size of the increments and decrements should be decreased and the procedure repeated. It may well be that because of the nature of the variables involved, this size cannot be further decreased. In this case, the "true" optimum may not be reached and the procedure ends with an "approximate optimum."

Strategy Followed and Results Obtained

Ten cross-correlated streamflow and demand series of 50 years each were generated using the first-order autoregressive model for monthly streamflow simulation summarized in the last section of Chapter V, for their routing through the reservoir and the computation of the SI_R and SI_p by the Corps of Engineers computer program. The strategy used was as follows:

1. For the "optimal" values of E, Y, and R as given by the linear programming solution to the deterministic case, compute the SI_R and SI_p values. If they are less than 0.1585 and 0.05 respectively, initiate the incremental analysis.
2. If SI_R and SI_p are greater than these values, find the extreme values from which to start the incremental analysis: using E as given by the linear programming results, a fixed R, and Y as the maximum feasible storage; and using Y as given by the linear programming results, a fixed R, and the E for which the present value of benefits would equal the

present value of the costs. Find the SI_R and SI_p for these extremes and, according to these results, start the incremental analysis from one or both these extremes.

Each time, the simulation was started assuming an empty conservation storage space. It was found that by using both sets of values: E , Y , and R as given by the linear programming; and E and R as given by the linear programming and the maximum feasible Y , the shortages were above the maximum acceptable values. The value of R was then arbitrarily set equal to 30,000 Ha and the search started from both ends until the SI_R and SI_p were within acceptable limits. The incremental analysis was then performed at both starting points, finding that the "maximum" value of the objective function was then $Y = 1110 \times 10^6 m^3$, P = 155,000 Kw ($E = 730 \times 10^6$ kw-h) , $SI_R = 0.1171$, and $SI_p = 0.0376$. This "maximum" value was $Z = Q\ 156.54 \times 10^6$ from Equation (6.6) and Figures A.9 to A.13 of the Appendix.

Similarly, using the broken-line model for streamflow simulation summarized in the last section of Chapter V, 10 series of 50 years each were generated and the optimization-simulation procedure repeated to give "optimum" values of $Y = 1540 \times 10^6 m^3$, P = 145,000 kw ($E = 682 \times 10^6$ kw-h) , $SI_R = 0.1467$, and $SI_p = 0.0355$. The corresponding "maximum" value of the objective function was $Z = Q\ 141.47 \times 10^6$.

CHAPTER VII

ANALYSIS OF THE EFFECT OF DATA LIMITATIONS

Data limitations in developing countries affect water resources project designs in three major areas: The use of policy guidelines to accomplish the development aims of the country, the choice of models to represent the real world, and the estimation of the parameters of the model once it has been chosen. These factors affect the designs with different degrees of importance in terms of a given measure of project performance.

In this chapter, the relative effect upon the "maximum" present value of net economic benefits of various factors is discussed. These factors are the choice of a deterministic linear optimization model, the choice of deterministic irrigation demands, of stochastic correlated and uncorrelated supply and irrigation demands, the choice of the model to represent the autocorrelation structure of the stochastic component of streamflow series, of errors in the estimation of the basic economic and hydrologic factors once a model has been selected, and of policy guidelines which may be expressed as constraints in the optimization process. This discussion is based on the results obtained in previous chapters and on additional analyses.

To organize the presentation, a general discussion of the meaning of changes in different parameters is first made in terms of a sensitivity analysis based on a linear programming formulation. Then, following the division presented in the first lines of this paragraph (although not in the same order), the material is divided into three parts:

1. The effect of the choice of different types of models.
2. The effect of the uncertainties introduced by the estimation of the parameters of the model.
3. The significance of policy guidelines, including the economic model chosen for the economic appraisal of the project.

Sensitivity Analysis

The analysis of the effects of the different factor can be aided by analyzing how the different coefficients of a general linear programming formulation affect the optimal solution. Using matrix notation the general (maximization) linear programming problem can be expressed as follows:

$$\left.\begin{array}{l} \max\limits_{\underline{x}} \{f(\underline{x})\}; \text{ subject to: } A\underline{x} \leq \underline{b} \\ \qquad\qquad\qquad\qquad\qquad\quad \underline{x} \geq 0 \end{array}\right\} \tag{7.1}$$

in which (56):

$A = [a_{ij}]$, $i = 1,2,\ldots,m$, $j = 1,2,\ldots,n$; in which the element a_{ij} is the "<u>structural coefficient</u>" in the ith row and jth column.

$\underline{b}$ is the column vector of the m "<u>stipulations</u>" b_i , $i = 1,2,\ldots,m$.

$f(\underline{x}) = \sum_{j=1}^{n} C_j x_j$; in which the C_j are called "<u>cost coefficients</u>".

The effect of changes in the structural a coefficients, stipulations b , and cost coefficients c can be summarized as shown in

Table 7.1. From this table and from the linear programming model presented in Chapter IV as Equations (4.11) and (4.12), the following observations can be made with respect to the demands, supply, and economic parameters.

1. Irrigation demands for each period (r_t) are structural coefficients in the A matrix. They are also stochastic in nature, as discussed in Chapter V. The changes introduced in r_t by its stochastic nature may be capable of making the values of the original basis no longer optimal, of making the original basis no longer optimal, or of making the solution obtained by the deterministic model infeasible, depending upon the magnitude of these changes. In the first case, only an adjustment of the "optimum" value of the objective function needs to be made. The second case introduces a bias in the deterministic solution, and the third case may cause a complete failure of the deterministic solution.

   In the section about the choice of the model later in this chapter, the results of an investigation of whether the stochastic effect of irrigation demands may fall within the first or third cases are discussed. The second case was not considered since it was desired to keep both irrigation and hydropower in the stochastic model. If constraint Equation (4.9) is found to be active, it should be added to the set of Equations (4.11). If that were the case, then the operation and maintenance unitary costs and unitary capital costs of both the power plant and the reservoir also become structural

TABLE 7.1

Classification of the Effect of Changes in the Structural Coefficients, Stipulations, and Cost Coefficients (1)(56)

Those who may change the original optimal basis*.		Changes in "a" coefficients of nonbasic variables. Changes in "a" coefficients of basic variables, (may also prevent the obtention of feasible solutions). Changes in "c" coefficients.
Those who may not change the original basis but:	May change the value of the original basic variables.	Changes in "a" coefficients of the original basic variables. Changes in "b" coefficients (may also prevent the obtention of feasible solutions).
	May not change the value of the original basic variables.	Changes in "a" coefficients of nonbasic variables. Changes in "c" coefficients (changing the value of the objective function if they correspond to original basic variables).

* The optimal basic solution is given by that set of values for the basic variables that optimizes the objective function. The basic variables are those which form a solution and whose value is not zero

coefficients. A change in these unitary costs could then produce any of the effects previously discussed for the irrigation demands for each period, independently of whether the model used is deterministic or stochastic.

2. The flows for each period are stipulations. Changes introduced in these stipulations because of their stochastic nature may either change the value of the original basic variables or cause the deterministic solution to be infeasible. These effects are discussed in the section about the choice of the model. Similarly, policy guidelines which may be introduced as constraints in the model (whether deterministic or stochastic) are stipulations. Examples of these are the right-hand side of constraints expressed by Equations (4.9) and (4.10), and the allowable shortage indices specified in Chapter VI.

3. All unitary costs and prices and the parameters of the economic model (see Equations (2.15), (2.16), and (6.2)) can be reduced to cost coefficients (see Equation (6.6)). If a change in these is sufficiently large, the original optimal basis may be changed. Otherwise, only the "optimum" value of the objective function needs to be recalculated, which is not a difficult task as will be discussed in the section about erroneous estimation of the parameters of the model. How the choice of the economic model for the economic appraisal of the project can be traced to a change in the cost coefficients is also discussed in the section about the significance of the economic model.

Choice of the Model

As it was discussed in Chapter I, models are only idealized representations of the "real world." Scarcity of basic data may induce the planner to disregard the relationships between certain components of the system, i.e., to use a "traditional" rather than a systems analysis model. If a systems analysis approach is nevertheless chosen, it may induce him to make a wide range of assumptions, including linear relationships and deterministic outcomes. These assumptions may be made in the overall model (for example, the choice of a deterministic linear programming optimization model) or in certain components of the model (for example, the use of deterministic demands). Even if a stochastic model is chosen, the planner may find himself in a position where short records make it difficult for him to decide upon the model to simulate stochastic sequences (for example, the model to simulate streamflows).

Whether he uses the "traditional" or a systems analysis approach, scarcity of data may also induce him to use inadequate models for the economic evaluation of the project and then try to qualitatively "account for" the inadequacies of the economic model. If he uses a "traditional" approach, the effects of these inadequacies may not become apparent to him.

Using the stochastic model presented in Chapter VI, the relative effect of choosing a "traditional" approach, of using a deterministic linear programming model, of using a stochastic model with deterministic irrigation demands, of using a stochastic model with independent supply and irrigation demand sequences, and of using a model which preserved

an apparent long-term memory of the stochastic component of streamflow sequences, was investigated. For this purpose it was assumed that all other factors were known with certainty and that the "true" streamflow and irrigation demand sequences were represented by the cross correlated first-order Markov model described in the last section of Chapter V. The procedure used was as follows:

1. Ten sequences of 50 years each (monthly flows) were generated using the procedures described in Chapter V, to obtain independent flows and irrigation demands, and to obtain streamflow sequences with a long-term memory in the correlogram of residuals.

   Two series of deterministic monthly irrigation demands were obtained, first using the mean monthly precipitation data given in Table A.2 of the Appendix and, second, using the mean monthly values of the precipitation data used to generate the stochastic demands (from station Cubilgüitz). In both cases the traditional procedures described in Chapter II were followed.

2. These combinations of independent demands and supply, deterministic demands and original Markovian stochastic supply, and broken-line stochastic supply and original stochastic demands, were routed through the "true optimal" solution obtained by the original Markovian dependent stochastic model, and their effect ascertained by the changes in the shortage indices SI_R and SI_p (see Equation (6.8)). To evaluate the type II error involved in the choice of the model for representation of the stochastic component of streamflow sequences, the original

Markovian stochastic flows and stochastic demands were also routed through the "optimal" solution shown at the end of Chapter VI for the broken-line streamflow model. The results are in Table 7.2.

Several considerations can be made based on the results shown in Table 7.2. It is convenient, however, to first indicate that once a maximum value has been selected for the allowable SI_R and SI_p (see Equation (6.9)), any result which exhibits a SI_R and or SI_p greater than this maximum (0.1585 and 0.05 in the present case) has to be considered infeasible, no matter what the absolute values of SI_R and SI_p are. In some instances, however, the comparison of these absolute values can give a clue as to the relative effect of different models or changes in their coefficients. The considerations that can be made are as follows:

1. The use of deterministic models may give rise to projects that may fail when operated under real stochastic conditions, as can be seen in rows 1 and 2 of Table 7.2. A comparison of these two rows may give the impression that the "traditional" method would produce results that are "less wrong" than those given by the linear programming model. Although this is true for the present case, a generalization cannot be made because the 24,700 Ha of land used for the "traditional" approach represented the actually available land in the area, whereas a high limit was arbitrarily set for the linear programming model (see Chapter IV). Would this limit have been set for the "traditional" approach, it is likely that an area much greater than 24,700 Ha would have been chosen based on the

TABLE 7.2

Relative Effect of the Choice of the Model

Model			Y ($10^6 m^3$)	P (10^3Kw)	R (10^3Ha)	SI_R	SI_P
(1) Results from the "traditional" approach (Ch. III), evaluated using stochastic Markovian flows plus stochastic irrigation demands.			1060	175	24.7	0.0756	0.1004
(2) Results from the deterministic linear programming model (Ch. IV), evaluated using stochastic Markovian flows plus stochastic irrigation demands.			846	177	62	10.6276	2.4763
Results from the stochastic model (Ch. VI) and stochastic Markovian flows plus dependent stochastic irrigation demands evaluated using:	(3) Independent stochastic flows and irrigation demands.		1110	155	30	0.2309	0.0793
	(4) Deterministic irrigation demands	Using average precip. over the area	1110	155	30	0.1894	0.0450
		Using average values from station Cubilgüitz	1110	155	30	0.1130	0.0371
	(5) Broken-line stochastic flows.		1110	155	30	0.9986	0.2940
	(6) Stochastic Markovian flows plus dependent stochastic irrigation demands, i.e., the "true optimum."		1110	155	30	0.1171	0.0376
	(7) Stochastic Markovian flows with independent stochastic component ($r_1 = 0$).		1110	155	30	0.0	0.0051
(8) Results from the stochastic model (Ch. VI) and stochastic broken-line flows plus original stochastic irrigation demands, evaluated using stochastic Markovian flows plus dependent stochastic irrigation demands.			1540	145	30	0.0583	0.0240

deterministic demands for irrigation, and thus the shortage would probably have been much greater.

These results, however, do indicate that in relatively simple cases, such as the one considered in this work, it may not be worth the effort to try to get a first approximation to the "optimum" by using a deterministic linear programming model, unless additional information is desired to be used as a guideline for other analyses (such as was done in the section on sensitivity analysis earlier in this chapter). If no such additional information is required, it would be better to simply obtain a design by the "traditional" approach and use it as a starting point in the optimization by simulation.

These results also point out that the combined effect of the assumed linearity, the use of average values for the supply and demand sequences, and the use of long periods over which these average values are obtained, may prove to be quite misleading if the effort in using the systems approach ends with the solution of a deterministic linear programming problem. If the effort stops there, these results may not be better than those that could be obtained by the "traditional" approach.

2. Getting into the stochastic model, a comparison of rows 3, 4, and 6 of Table 7.2 will give some light as to the effects produced by the demands. Again, some considerations must be previously made in order not to make an erroneous interpretation of these values. It cannot be concluded, for example, that because the shortages are greater, the use of independent

demand and supply series is more critical than the use of dependent supply and demand series. It must be remembered that the lag-zero cross correlation coefficient used was rather low (see Chapter V) and this may have had some influence in the results.

On the other hand, even if it is logical to think that the case of correlated demands and supply (less supply, less rainfall and thus more irrigation demand) should be more critical than the uncorrelated case, it should be remembered that an important factor is probably being overlooked. This factor may be the effect of the timing of the demands with respect to the available supply. This may work in an opposite direction from the correlation between the series. For example, correlated demands may be higher but, by the same token, they will tend to follow the same variations of the supply. Uncorrelated demands may be smaller but may occur at any time, and it may be that this effect will overshadow the other one, especially for small values of the cross correlation coefficient. Factors such as the type of crops and the cropping pattern may thus be of importance.

A comparison of the values of row 4 is also of interest. The upper values in this row were obtained using the estimated average rainfall over the project area to compute the monthly irrigation demands, and the lower values were obtained using the monthly rainfall averages for station Cubilgüitz, whose record was used to generate the stochastic demands. The two

series of average monthly demands obtained (in m^3/sec) are respectively (from May to April): 0.0, 0.0, 33.0, 106.0, 0.0, 0.0, 0.0, 0.0, 80.0, 124.0, 163.0, 103.0; and 0.0, 0.0, 34.0, 88.0, 0.0, 0.0, 0.0, 0.0, 57.0, 127.0, 108.0, 110.0. Although the use of the latter deterministic demands did not introduce a major effect in the shortages (as a comparison of the lower portion of row 4 and of row 6 indicates), the use of the former deterministic series did produce a SI_R greater than 0.1585, thus indicating that the results may be more sensitive to the distribution of the average values of monthly demands than to their stochastic nature. This, however, may also depend on the relative variance. These latter results also indicate that a change in the crop consumptive use and the effective precipitation (as a percentage of total precipitation) may be of importance, since a change in these values would produce a similar effect.

As far as the demands are concerned then, these results do not give any definite answers but rather raise more questions. These questions refer to the relative effects of the timing of the demands as opposed to the effects of the cross-correlation between supply and demand (for different values of the cross-correlation coefficient), of deterministic demands, of the consumptive use, of effective precipitation, and of the different parameters used to generate stochastic demands. It is believed that more research is needed in this area.

3. The effect of errors involved in the choice of the model by which to generate the streamflow sequences can be examined

in the light of the results shown in rows 5, 6, 7, and 8 of Table 7.2. In the first place, a comparison of rows 6 and 7 indicates, as would have been expected, that autocorrelated flows would require greater storage reservoirs for the same demands than serially uncorrelated flows. The important implication of this comparison is that the choice of the model could have determined whether flows would have been generated with $r_1 = 0$, or with $r_1 = 0.623$ as was actually done*.

Although no stochastic optimization was carried out using streamflow sequences with $r_1 = 0$, the values of row 7 indicate that a more optimistic design would have been obtained (i.e., smaller reservoir and or larger power plant). Since the routing of broken-line flows through the "optimum" design obtained using a lag-one Markovian model produced unacceptable shortages (see row 5, Table 7.2), it would be reasonable to expect that even larger shortages would have been obtained if this routing would have been made through the more optimistic design obtained by the use of serially uncorrelated flows. Therefore, it can be said that there may be cases where the type II error of a sum of harmonics model may be greater than the type II error of a model that uses 12 monthly historical values to incorporate the cyclic variation in the means and standard deviations.

With respect to the type II error of this latter model and the broken-line model, a comparison of rows 5 and 8

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* Refer to the section about the cyclic components in Chapter V as to how a value of $r_1 = 0$ could have been used if a sum of harmonics model would have been chosen.

indicate that the consequences of choosing the Markovian model are greater than the consequences of choosing the broken-line model. The "optimum" present value of net benefits from the Markovian model is given in Chapter VI as Q 156.54 x 10^6 and that from the broken line model as Q 141.47 x 10^6. If the broken-line model is chosen erroneously, the economic benefits that are obtained are Q 142.31 x 10^6 (because SI_R and SI_p are 0.0583 and 0.0240 if the Markovian model flows are used, instead of 0.1467 and 0.0355 as indicated for broken-line flows in Chapter VI). The benefits foregone are then equal to Q 156.54 x 10^6 - Q 142.31 x 10^6 = Q 14.23 x 10^6. If on the other hand, the Markovian model is chosen erroneously, the project "fails" because SI_R and SI_p are greater than 0.1585 and 0.05. The economic measure of that failure is hard to ascertain, but it is likely to be greater than the value computed simply by using the SI_R and SI_p of 0.9986 and 0.2940 (which, just for the record, is Q 17.81 x 10^6).

These results show that an investigation of the economic effect produced by the type II error of the different models, can be used to counteract in part the effect of the uncertainty caused by data limitations. In the present case, for example, the use of a broken-line model is the "least risky" decision for choosing the model.

Erroneous Estimation of the Parameters of the Model

Two types of parameters were considered: the economic parameters and the hydrologic (streamflow) parameters. As stated in the section about sensitivity analysis earlier in this chapter, the economic parameters can be reduced to cost coefficients and the effect of a small change in them can be directly evaluated. This is done in the second part of this section. The relative effect of the hydrologic parameters, however, has to be made by simulation because of the nature of the objective function (Equation (6.5)).

Hydrologic (Streamflow) Parameters: Keeping the assumption made earlier, i.e., that the "true" streamflow sequences were those represented by the lag-one Markov model, as described in Chapter V, the effects of small changes in its parameters were evaluated based on the "true optimum" design (row 6 of Table 7.2). For this purpose, a 10 percent change was made in the long-term mean of the historical sample (decrease), in the standard deviations (increase), and in the first-order autocorrelation coefficient (increase). Using the model developed by Matalas (51), 10 series of 50 years each were generated in each case, and the routing procedure previously described was repeated. The results are shown in Table 7.3.

Table 7.3 indicates that while a 10 percent increase in the first-order autocorrelation coefficient will somewhat decrease the present value of net benefits, no "failure" occurs. On the other hand, a 10 percent decrease in the long-term mean and a 10 percent increase in the standard deviations are liable to produce a "failure." Furthermore,

the relative effect of the change is greater for the long term mean. It is interesting to note this relative sensitivity since, as it has been stated before, the relative inaccuracy with which these parameters can be estimated and the relative difficulty with which the accuracy can be increased by regional analysis follows precisely an inverse order, i.e., serial autocorrelation coefficient, standard deviations, and means.

TABLE 7.3

Relative Effect of a 10 Percent Change in the Hydrologic (streamflow) Parameters

	Y ($10^6 m^3$)	P (10^3Kw)	R (10^3Ha)	SI_R	SI_p
"True optimum"	1110	155	30	0.1171	0.0376
Ten percent decrease in long-term mean	1110	155	30	0.7445	0.3337
Ten percent increase in standard deviations	1110	155	30	0.2723	0.0557
Ten percent increase in the first-order auto-correlation coefficient	1110	155	30	0.1159	0.0435

Economic Parameters: The change in the "optimum" value of the objective function (see Equation (6.6)) produced by a small change in a cost coefficient (all other factors constant) can be evaluated by the partial derivative of the objective function with respect to that cost coefficient. This will be valid only for the point corresponding to that "optimum" value. However, if the response surface in the vicinity of the "optimum" is relatively flat, this partial derivative

will be an acceptable approximation in the neighborhood of that point.

Following this criterion, the relative effect of a 10 percent change in the overall cost coefficients of Equation (6.6) was obtained. The same procedure was applied to find the effect of a 10 percent change in several components of these cost coefficients, such as the unitary costs and benefits and the social capital productivity rate* θ_g (see Equation (2.15) and (6.6)). The results are shown in Table 7.4. Several observations can be made with respect to these results:

1. Whenever a cost coefficient or parameter involves a sum of components of the same sign (such as C'_p, C'_y, and the social unitary energy value 0.432), the effect of a change in it is greater than the effect of a change in its components. If a sum of components of different sign is involved (such as in C'_R and θ_g), the effect is smaller, as might have been expected.

2. The effect of changes in the economic parameters of the features of the project varies according to the relative importance and size of these features, also as might have been expected. The effect of a change in the social capital productivity rate θ_g can be considered in the category of the effects produced by changes of the parameters related to the most important features of the project (reservoir and power plant in this particular case).

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* Of all the parameters of Equation (2.15), θ_g was the one found more difficult to estimate for the example used in this work, as discussed in section A.5 of the Appendix.

3. The effect of a relatively small single change in the overall cost coefficients and their components can be considered to change the "optimum" value of the objective function, but not enough to change the values of the original basic variables or to change the original basis, if all these components appear only in the objective function.

The effect of this change in some of them (such as the social unitary value for energy, monetary energy price, θ_g, and unitary capital cost of the reservoir, for example) may be equally or more important than an equivalent change in certain hydrologic parameters (such as the first-order autocorrelation coefficient), but less important than an equivalent change in others (such as the mean and standard deviation, for example). In general, this effect can be considered less critical than that produced by a similar change in the hydrologic parameters (see Table 7.3) and less critical than that produced by the choice of the model (see Table 7.2).

It must be remembered, however (although this aspect was not investigated), that if these parameters also appear in constraints which are active, such as that of Equation (4.9), for example, they become structural coefficients. A small change in them may then cause a wide range of effects beyond a simple change in the "optimum" value of the objective function, as discussed in the section about sensitivity analysis at the beginning of this chapter.

TABLE 7.4

Relative Effect of a 10 Percent Change in the Overall Cost Coefficients and in Selected Components of These Coefficients (refer to Equations (2.15), (4.2), and (6.6)).

	Parameter	Effect (in $Q \cdot 10^6$)
Overall cost coefficient	C'_R	0.042
	Social unitary energy value = 0.432*	31.500
	C'_p	5.140
	C'_y	7.750
	K_R (and b_R)	0.021
	K_p (and b_p)	0.237
Components of the overall cost coefficient	B_R	1.480
	O_R	0.590
	C_R	0.875
	O_p	1.650
	C_p	3.500
	O_Y	0.088
	C_Y	7.640
	Monetary energy price = 0.018*	11.100
	θ_g	11.000

* These values are related by 0.432 = [0.277 + 8.6 {0.018}] as shown in Equation (4.2). The right-hand side of this expression comes from the evaluation of the social value of net income received by the industrial sector (considered as the difference of the energy price from "without" to "with" project conditions), of the social value of the revenue received by the government from energy sales, and of the effect on the balance of payments of the income received by the industrial sector (see section A.5 of the Appendix, and Equations (2.7) to (2.13)).

Significance of the Economic Model and Policy Guidelines

As was stated at the beginning of this chapter, scarcity of basic data may affect the design of water resources projects by the adoption of certain policy guidelines. For example, the systems approach may not be attempted and projects may be economically evaluated using traditional approaches (see Chapter II) or, even if it is used, these traditional approaches may be imposed as restrictions because of the skepticism of international lending institutions in the face of unreliable data. Certain policy guidelines, such as an upper limit to the losses in terms of the allowable percentage of the annual gross benefits (see Chapter VI), may also be affected by unreliable data. These aspects are discussed in this section.

Significance of the Economic Model: The significance of the traditional approach and of Mobasheri's approach (see Chapter II) is discussed first. This discussion is considered necessary to set the stage for the analysis of the effect of the choice of the economic model.

The Traditional Approach: Mostly because of lack of basic information, as already discussed, benefit-cost analysis in developing countries is traditionally done by considering only direct benefits and costs at market prices and, based on the results obtained, qualitative considerations on the part of the decision makers weight the desirability of the project in terms of how it will contribute to things such as the balance of payments, income distribution, etc. At most, the only factor that is explicitly taken into account is the scarcity of capital for investment. This is done, as previously

discussed, by specifying that the project must give a rate of return which is set equal to a value higher than the market rate (for example, 12 percent). In this manner, only the social cost of the capital is explicitly accounted for.

It is of course logical that if capital is scarce, the government should want to invest only in those projects whose rate of return is the highest. However, by applying the criterion outlined above, the ranking of projects is done based explicitly only on a national-income increase basis and an incorrect one, since market prices are used for costs and benefits. Furthermore, by specifying a high rate of return, the objective function favors less capital intensive projects which is contrary to the needs of a developing economy. The net result is that even if goals such as the distribution of income, an equilibrium in the balance of payments, and an improvement of the unemployment situation appear in the development plans of a country along with the increase of the per-capita income, the traditional method only ranks projects in terms of returns from the investment. Thus, even if this is not the intention, projects which may contribute very little to those developing goals or that may even be detrimental to those goals, may be favored.

The Alternative Approach: As has been discussed, an objective function such as the one proposed by Mobasheri takes explicitly into account the mentioned goals. As can be seen from the equations presented in Chapter II, this model accounts for the social cost of the capital by using a social capital productivity rate θ_g , and also accounts for the social cost of underemployed labor and foreign exchange by the use of shadow prices. On the benefit side, it includes

the social value of the net revenue obtained from the operation of the project by means of the rate θ_g , and the social value of the additional income received by the different sectors of the economy by tracing the portions of it that are consumed and reinvested, and by using a social discount rate r as a measure of the social time preference.

The need for capital-intensive projects to increase future per-capita income is taken into account by making r dependent upon the difference between the rate of growth of the total national product, and the rate of growth of the population: the smaller this difference, the smaller r is and the more capital intensive the projects are, and vice-versa. By explicitly including in the objective function a term which accounts for the effect of the project upon the balance of payments, a model such as this one will favor those projects which require less imported capital goods.

Finally, the model, while striving for an overall capital intensive project and for increasing the national income, will also provide for a distribution of the income favoring the local agricultural sector, and for the use of underemployment labor in that sector. This is accomplished because <u>it gives different weights to the social value of income received by the different sectors of the economy</u>. Consider, for example, the way in which it would allocate funds between irrigation (the agricultural sector) and hydropower (the industrial and power sectors):

The social value of benefits at period t would be (see Equations (2.7) and (2.8)):

$$V_t + G_t = \sum_{i=1}^{n} \{[(1-\mu_i)\eta_i](1-P_i) + \frac{\rho_i}{r}[1-(1-\mu_i)\eta_i](1-P_i)\}b_i + \theta_g \sum_{i=1}^{n} P_i b_i \tag{7.2}$$

in which all the terms are as previously defined in Chapter II. This expression can be written as:

$$V_t + G_t = W_R\, b_R + W_p\, b_p \tag{7.3}$$

in which b_R and b_p are the benefits from irrigation and from power, and the weights are given by:

$$\left.\begin{aligned} W_R &= [(1-\mu_{ag})\eta_{ag}](1-P_{ag}) + \frac{\rho_{ag}}{r}[1-(1-\mu_{ag})\eta_{ag}](1-P_{ag}) + \theta_g P_{ag} \\ W_p &= [(1-\mu_I)\eta_I](1-P_I) + \frac{\rho_I}{r}[1-(1-\mu_I)\eta_I](1-P_I) + \theta_g(P_I+P_p) \end{aligned}\right\} \tag{7.4}$$

in which the subscripts ag , I , and p stand for agriculture, industry, and power, respectively.

In a developing country, it is not uncommon to find in the <u>agricultural sector</u> a low income elasticity of demand η_{ag} (because the goods consumed are necessities), a relatively high average propensity to save μ_{ag} , a low percentage P_{ag} of the benefits returned to the government as revenue, and a moderate average rate of return on capital ρ_{ag} . In the <u>industrial sector</u> μ_I is low, η_I and ρ_I are high, although P_I may be zero if the benefits are assumed to be the difference in energy price from "without" to "with" project conditions, multiplied by the percentage of the energy consumed by the industrial sector. For the <u>power sector</u> P_p is one, and the benefits are the revenues from the power sales. If these values are, for example, those

shown in Table 7.5, the weights W_R and W_p are 2.333 and 0.39 for an r of 4.3 percent, and θ_g equal to 1.22. This would mean that a dollar (gross benefit) received from irrigation is valued about six times more than a dollar received from hydropower, in terms of income distribution.

TABLE 7.5

Example of Coefficients of the Alternative Economic Model Estimated for the Guatemalan Economy

Coefficient	Sector		
	Agriculture	Industry	Power
η	0.5	1.72	-
μ	0.5	0.13	-
ρ	0.15	0.20	-
P	0.25	0.00	1.0

Effect of the Choice of Economic Model: The dilemma of the planner in a developing country is that he may be faced with the following situation: To use a model such as the one proposed by Mobasheri is attractive because it takes into account the market imperfections of a developing economy and explicitly includes in the objective function the main goals for development. On the other hand, the data requirements of such a model may be excessive for a developing country, and many assumptions may have to be made. Furthermore, it is likely that the funds for this type of project must be sought abroad, from international financial institutions. As stated by King (8), these

institutions may be skeptical of such a model because of data limitations, and may insist on the traditional approach.

In the example followed through using data from Guatemala, the "optimum" scale of development for the irrigation and hydropower project was obtained using Mobasheri's model (Chapters IV through VI). Using the sizes of the structures obtained with the deterministic model, a benefit-cost analysis by the conventional approach was then made. It was found that the internal rate of return of the project was between 11 and 12 percent. If the same analysis were to be performed with the results from the stochastic model, the rate of return would be less than that because the reservoir size is bigger and the power generated is less than those obtained from the deterministic model.

If, following the traditional approach, a minimum rate of return of 12 percent would have been set to account for the social cost of capital, there is a chance that this project might have been rejected in favor of an alternative project whose return to the investment was at least 12 percent. The social cost of this decision, in terms of social benefits foregone, would be equal to the "maximum" present value of net social benefits that could have been obtained by the construction of this project, minus the "maximum" present value of net social benefits of the alternative project, evaluated using the same criterion (Mobasheri's model in this example). The alternative project is justifiable, in terms of the developing aims of the country, only if this difference is zero or negative. In other words, the rate of return criterion should be secondary to the explicit consideration of how the project contributes to the developing goals of the country,

rather than the qualitative consideration of this adequacy being secondary to the rate of return criterion.

This would give a firmer basis on which to negotiate the needed foreign currency loans. If the lending institutions insist on the traditional approach, this would still allow for evaluating the effect of this constraint and thus favor those investments that, while meeting the minimum rate of return requirement, would either give the highest social net benefits, or the lowest social cost (as social benefits foregone) in terms of the country's developing objectives.

If data are scarce, the criterion proposed by Maass (57) could be followed. This is to say, that by a political process certain criteria are set, and then the ranking of projects is done following those criteria. For example, in the present case, the government or the planning institution could establish different sets of criteria with values for the social discount rate r, the social capital productivity rate θ_g, and the relative weight to be given to the social value of the benefits received by the different sectors of the economy. Then, either a set is chosen by a political decision and the project "optimized" accordingly, or several "optimum" scales of development are obtained with the different sets, from which the decision makers may choose with a knowledge of the economic consequences of their choice, in terms of the developing aims they themselves have established.

The effect of the choice of the economic model in the systems analysis approach can be traced to a change in the cost coefficients of the objective function. In the case just discussed, if the "optimum"

scale of development for this project would have been searched using an objective function structured in the conventional manner and with a discount rate of 12 percent, all the cost coefficients would probably have been negative, indicating the infeasibility of the project by that criterion.

If the minimum internal rate of return chosen is such that an "optimum" scale of development is liable to be found by the use of that rate as a discount rate in an objective function structured in a conventional manner, the effect may be just to change the optimal basis obtained by the use of an economic model such as Mobasheri's. This was the case, for example, when the cost coefficients near the optimal solution of the deterministic model (i.e., R = 62,000 Ha, E = 910.79 x 10^6 Kw-h, and Y = 846 x $10^6 m^3$) were evaluated using both Mobasheri's model ("model I" in Table 7.6) and the conventional model with a discount rate of 9 percent ("model II" in the same table). Since the coefficient for irrigation became negative, model II would have eliminated it, thus changing the original basis.

TABLE 7.6

Comparison of the Cost Coefficients in the Objective Function Obtained With Economic Models I and II for a Given Size of the Elements R, E, and Y.

Model	Coefficient for Irrigation	Coefficient for Energy	Coefficient for the Reservoir size
I	4.0	0.378	-0.06812
II	-68.4	0.125	-0.0573

Choice of the economic model may also exert an influence on the effect of the cost coefficients upon the measure of project desirability. A model such as Mobasheri's, for example, may give a larger scale of development than a conventional economic model, thus increasing the effect of a change in the cost coefficients.

Policy Guidelines: The choice of the minimum rate of return discussed in the previous section is a policy guideline. Its effect upon the economic measure of project desirability can be traced through the effect of the choice of the model. If this minimum rate is 12 percent, for example, the effect of choosing the conventional economic model may be to make the project infeasible and to invest in an alternative project, with the economic implications already discussed. If the minimum rate is 9 percent, for example, the effect would be to change the original basis. The economic implications of optimizing with this conventional model could then be evaluated in a manner similar to that suggested in the previous section.

The requirements that the energy price must not be greater than Q 0.018/Kw-h and that the net rentability of the power entity must not be less than 9 percent (see Equations (4.9) and (4.10)) are also policy guidelines. Since they are stipulations, the effect of a change in them may be either to change the value of the original basic variables or to cause infeasibility. The inclusion of these policy guidelines as constraints, may also indirectly produce infeasibility since the unitary costs become also structural coefficients, as already discussed. Although in the former case the infeasibility cannot be directly attributed to lack of data, in the latter case it is produced

by errors in the estimation of the costs, and indirectly introduced by the policy guidelines.

Similarly, the policy guideline that the losses, expressed as a percentage of the gross annual benefits, must not exceed 1.5 and 1.0 for irrigation and power respectively, are stipulations. As was shown in Chapter VI, these limits can be transferred to the shortage indexes SI_R and SI_p by the use of Equations (6.2) and (6.8). The use of these equations make the limits for SI_R and SI_p dependent upon the values of the average annual economic unit loss b and of the social capital productivity rate θ_g. A change in these last two factors may change these limits, so that the value of the variables in the optimal basis may change. Also, the effect of a change in a parameter (for example hydrologic) may then go from a change in the "optimal" value of the objective function all the way to infeasibility, or vice versa, as a consequence of a change in these factors. The effect of this kind of policy guideline is also dependent upon the model chosen for the loss function (see Chapter VI) with consequences similar to those discussed above. Although not caused by data limitations, similar consequences can be produced by the choice of R_s in Equation (6.4), which is also a policy guideline.

Final Remarks

The analysis and discussion presented in this chapter pertain to small changes in different economic and hydrologic factors, taken one at a time. In the "real world" however, it is likely that several of these effects may occur simultaneously. From the discussion presented in this chapter, it is also obvious that several interrelationships

exist among the effects produced by several factors. Examples of these are when the factors appear as a product, such as certain components of the cost coefficients. Policy guidelines and the choice of models are also interrelated with the effect produced by changes in certain factors as already discussed.

Another example is when a stochastic model is chosen instead of a deterministic one. In this case, the values of the design variables will be affected, thus influencing the effect of changes in the cost coefficients and their component elements. This may also cause previously inactive constraints to become active with all the implications involved (for example, constraint Equation (4.9) may become active with the unitary costs of the reservoir and power plant becoming structural coefficients).*

With respect to the relative effect of errors in the estimation of the parameters of a chosen model, only the sensitivity of the optimization model with respect to small changes (10 percent) in these parameters was investigated. It must be remember, however, that the reliability with which these different parameters can be estimated varies with each one. Thus, the uncertainty introduced by errors in these parameters is really a combination of both the response of the optimization model (what was investigated here) and the variability of each parameter.

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* When constraint Equation (4.9) was checked with the values of P and Y given by the stochastic model of Chapter VI, it was found that an energy price of Q 0.019/Kw-h was needed to give a net rentability of the power entity equal to 9 percent, i.e., that with a price of Q 0.018/Kw-h a net rentability lower than 9 percent is obtained. In order to fulfill this constraint, probably it would have been necessary to abandon irrigation or to make it small enough so that the operation rule of the reservoir simulation computer program would release water based only on the power demands.

The most distinguishable characteristic of the world we live in is uncertainty, and it seems like not enough attention has been given to it in such uncertain endeavors as the planning of projects for developing purposes. The author believes that although data limitations in developing countries are a drawback for the design of water resources projects, they should not be an excuse for hiding the effect of these uncertainties by the use of models that may have less data requirements at the expense of too much distortion of reality. As an example, the results reported herein show that ignoring the stochastic nature of supply can cause designs that may fail to produce the desired results, with serious economic consequences. Similarly, that the type II error can be used as a basis for selection of the streamflow simulation model to diminish the economic effect of the uncertainty caused by data limitations.

The results of this investigation suggest a possible way to introduce a more rational safety factor in the operational designs. For example, the uncertainties that may be introduced by the estimation of the different parameters of an economic model such as Mobasheri's, might be avoided by reducing its most uncertain components to policy guidelines, as discussed in the section about the significance of the economic model. In this manner the effect of these and other policy guidelines may be made apparent to the decision makers by the use of the systems approach. Also, an "optimistic," a "most probable" and a "pessimistic" estimation of the unitary costs and benefits of the components of the system that are liable to be the most important features in the project, may be made. By following the procedure of

assuming that these estimates follow a given probability density function (as done in reference (37) for the estimates of annual energy demands), a value with a given probability of occurrence might be chosen.

With respect to the choice of the hydrologic model, that model having the type II error which introduces the smallest effect should be selected. Once the model has been selected, that combination of parameter variability and optimization-model response which produces the greatest effect could be identified by the use of a shortage index, as used in the analyses reported in this chapter. Then, the effect of the sample available could be taken into account by making an interval estimation of this parameter and using perhaps the most unfavorable limit of this interval as a design parameter.

In the case of the losses produced by the stochastic nature of supply and demand, a way to avoid the effect of uncertain data (such as the b coefficient of Equation (6.2)) would be to design for zero losses. This, however, may prove to be more costly than coping with the uncertainty of these data.* Another way could be to specify the upper limit for the allowable average annual shortages instead of specifying it for the losses as a percentage of the annual gross benefits. In this manner, the effect of uncertain data (assuming the quadratic loss function is adequate) would only be that introduced by

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* For example, in the case investigated the reservoir, power plant, and irrigation area sizes had to be made equal to 846 x $10^6 m^3$, 70,000 Kw, and 30,000 Ha respectively in order to obtain zero values for SI_R and SI_p (SI_p was negligible). This is equivalent to a loss of Q 105.92 x 10^6, in terms of benefits foregone, with respect to the "optimum" design obtained in Chapter VI.

b as a cost coefficient, and not the most critical one produced by the policy guideline, as discussed in the section about policy guidelines. In this case, it is conceivable that the limit for the average annual shortages might be easier to determine (from a technical point of view) than the limit for the losses as a percentage of the annual gross benefits (from an economic point of view).

A next logical step following the research reported herein would be to further investigate and formulate all the interrelationships discussed in the first three paragraphs of this section, and to investigate procedures for the design of projects which, based on the information available, its reliability, and the relationships among the effects produced by changes in the different parameters, will enable the planner to "make the most of what he's got" whatever this might be. In this respect, it is believed that the use of systems analysis is not an unnecessary sophistication, but a very useful tool. It is also believed that the joint use of systems analysis and statistical decision theory is an avenue for this type of research which might be worthwhile to explore.

CHAPTER VIII

CONCLUSIONS

The objectives of this research specified in Chapter I, have been accomplished. From the results of the investigations and analyses performed, the following conclusions are drawn:

1. Data limitations in developing countries can affect water resource project designs in three major areas:
   a. The choice of the overall design model or parts of it.
   b. The estimation of the parameters of the model once it has been chosen.
   c. The choice of policy guidelines to accomplish the development aims of the country.

   In terms of a given measure of project performance (such as the present value of net economic benefits), the effect produced by choosing policy guidelines, including the economic model for the evaluation of the project, appears to be of uppermost importance, closely followed by the effect of the choice of the model. The effect of data limitations upon the estimation of the parameters of the model, in general, appears to be of less relative importance. This does not mean, however, that it should be disregarded.
2. Most policy guidelines can be viewed as constraints in the overall model, and the effect of limited data on their choice can easily produce infeasibility of the project. The effect of limited data on the choice of the economic evaluation model may lead to the selection of a project whose effect upon the economy of a developing country is contrary to the developing

aims of the country. The choice of the economic model may be traced to a change in the cost coefficients of the objective function. This change may be large enough to change the optimal basis found by using alternative models and, depending upon certain policy guidelines, the change may be large enough to make the project infeasible.

3. The model proposed by Mobasheri for the economic evaluation of projects was used as an example of the available alternatives to the economic model traditionally used for this purpose in developing countries. The data requirements of such a model appear more formidable than they really are. When applied to Guatemala, for example, the only real difficulty encountered was in the evaluation of the social capital productivity rate, θ_g . This and other parameters used in this model serve the purpose of evaluating the coefficients that introduce into the model the main goals for development, based on economic theory. Some of these coefficients, such as the relative weights to be given to the social value of income received by different sectors of the economy, may also be viewed as policy guidelines that the planning agency can set and whose effect on the project may be evaluated by the use of the systems analysis approach.

4. The use of deterministic linear optimization models may give rise to projects that may fail when operated under real stochastic conditions. In relatively simple cases, such as the one used as an example in this work, the use of such

models as a first approximation to the "optimum" (to be obtained by a stochastic model) may not be worthwhile. In such cases, the starting point for the stochastic optimization may well be obtained from a "traditional" design approach. The use of deterministic linear programming models can be justified if additional information is desired to be used as a guideline for other analyses (such as a sensitivity analysis, for example). If no such additional information is required and if the use of systems analysis ends with the solution of a deterministic linear programming model, the use of such a model may be quite misleading.

5. Not enough attention has been given in practice to the stochastic nature of the demands. The tests made to ascertain the effect of using deterministic, stochastic, dependent (to the supply), and independent irrigation demands were not conclusive. The results, however, seem to indicate that the timing of the demands with respect to the available supply, the distribution of the average values of the monthly demands, and the effect of stochastic consumptive use and effective precipitation percentages, are factors that should receive more attention.

6. The effect of the choice of the model by which to generate equally likely streamflow sequences is of importance. It is felt in the resultant autocorrelation structure of the generated series, which may range from an independent series to series which exhibit a long persistence effect, according to

the model chosen. The consequences of the type II error involved in the choice of the model may be great enough to produce infeasibility.

7. It is operationally feasible to use a broken-line model to preserve a long memory in the autocorrelation structure of the monthly streamflow residuals (obtained from the monthly streamflows by subtracting the mean of the month and dividing by its standard deviation), if their correlogram can be reproduced by the use of two broken-lines: one with a low frequency and the other with a high frequency. If the memory parameter of the high-frequency broken-line can be set equal to one, it is relatively easy to simulate streamflow sequences that reproduce a given number of historical streamflows, i.e., it is relatively easy to operationally simulate sequences that maintain a given long memory.

8. The results obtained seem to indicate that a long-memory correlogram of the streamflow residuals may be obtained from streams whose drainage area include karst topography. In such cases, the broken-line model may be a useful operational tool to preserve this long-term persistence. The broken-line model may also be a useful operational tool where the nature of the correlogram makes it difficult to decide upon the order of an autoregressive model to fit that process, or where too high an order has to be used if an autoregressive model is to be fitted to the process.

9. The economic effect of the type II error that might be involved in choosing a streamflow simulation model that generates series with short-term memory (such as a first-order autoregressive model or an independent model) is greater than the economic effect of the type II error that might be involved in chosing a model that preserves a long-term memory (such as a broken-line model). This is of special significance where short records make if difficult to ascertain the autocorrelation characteristics of the streamflow series.
10. The errors introduced in the estimation of the parameters of the model, once it has been chosen, in general can be considered to be more important when they are related to the hydrologic (streamflow) parameters than when they are related to the economic parameters that appear as (or that can be transformed to) cost coefficients in the objective function. When these same parameters appear also as structural coefficients, however, this statement cannot be made.
11. The first-order autocorrelation coefficient is especially difficult to estimate. All known estimators are biased downwards and this bias persists for sample sizes well beyond the longest streamflow records now available. It was found, however, that the relative effect of a small change in the hydrologic (streamflow) parameters is greater for the long term mean, followed by that for the monthly standard deviations and by that for first-order autocorrelation coefficient (if a first-order autoregressive model is chosen).

12. Although studied one at a time in the present case, it is unlikely that the effect of data limitations on the several factors considered will act independently in the real world. It is important to remember that several interrelationships exist among the effects produced on the various factors, in such a way that it would be proper to talk about and to investigate "direct" and "indirect" effects.

13. Not enough attention has been given to the problem of the many uncertainties introduced by data limitations in the planning of projects for developing purposes. In this respect, the use of stochastic systems analysis for planning water resources projects of certain importance in developing countries is not unnecessary sophistication, but a useful tool. It is believed that although data limitations do exist, there is a minimum amount of information that could be compiled in most developing countries to allow for the application of this approach. Both this approach and the "conventional" deterministic procedure are subject to uncertainties under these circumstances, but the stochastic systems analysis allows the planners to investigate the effect of these uncertainties as well as the effect of policy guidelines that they themselves may establish. In this manner, it provides a better path for "hedging" by accounting for the data limitations and by making the most out of the available information.

CHAPTER IX

RECOMMENDATIONS

From the analyses performed and the conclusions obtained from these analyses, the following recommendations are made:

1. For the economic evaluation of water resources projects in developing countries, the rate of return criterion should be secondary to the explicit consideration of how the project contributes to the developing goals of the country, rather than the qualitative consideration of this adequacy being secondary to the traditional rate of return criterion. An economic model that includes these goals should be used for that purpose.
2. If data are scarce, those coefficients of such a model that are most difficult to evaluate should be set as policy guidelines or criteria by a political process, in such a manner that the decision makers are aware of the economic consequences in terms of the developing aims of the country, of choosing a given set of coefficients. The planners should be aware that the choice of policy guidelines is what produces the greatest economic effect and should also be aware of the nature of this effect.
3. The use of linear deterministic models as the only tool to be applied in a systems analysis of a water resources project is not recommended. The stochastic nature of streamflow should always be accounted for in the model chosen for that purpose.

4. The stochastic nature of demands should receive more attention. Additional research is needed to determine the most significant components of models to generate equally likely sequences of the different types of demands. In the case of irrigation demands, for example, additional research is needed to ascertain the relative effect of correlation with the supply sequences, of the timing of the demands, of the crop types and patterns, and of the stochastic nature of consumptive use and percentage of effective precipitation. Similarly, more research is needed for stochastic simulation of other demands, such as energy and water supply.
5. In the case of optimization by simulation, more research is needed to evaluate the effect of the type of loss function used to account for the stochastic nature of both supply and demand sequences, and to chose the most convenient one.
6. Careful consideration should be given to the effect of the choice of the streamflow generation model, especially regarding its effect upon the autocorrelation structure of the generated series. It must be remembered that the popularity of a model does not guarantee its universal applicability. If data are limited, that model which produces a type II error with the smallest economic consequences should be used.
7. More research is needed on the estimation of the parameters of the broken-line model in order to make it fully operational. Its applicability to simulate streamflow sequences from karstic watersheds deserves additional study.

8. If a first-order autoregressive model is considered adequate for streamflow simulation, the use of Equation (5.2) is recommended for the estimation of its parameter θ_1 .
9. An effort would be worthwhile in developing countries to evaluate the data situation in relation to their applicability for the systems analysis of water resources projects. This approach should not be considered as unnecessary but as a versatile tool.
10. The determination of the "optimum" scale of development for a project should not be made without stating the probability of success or failure. It is recommended that planners be made aware of the economic effect of choosing different levels of this probability. For this purpose, a simulation procedure and the use of a loss function is recommended.
11. To diminish the effect of the uncertainties introduced by data limitations in the design of water resources projects by the systems analysis approach, the following measures are recommended:
    a. Reduce the most uncertain components of the economic model to policy guidelines, in order to make their effect apparent to the decision makers. For this purpose the planner should, if possible, construct utility tables (in terms of the developing goals of the country) for different sets of those components.
    b. If no additional information is available, an optimistic, a most probable and a pessimistic estimation of the unitary

costs and benefits of the principal components of the system should be made. This would at least allow for the estimation of a value with a given probability of occurrence if these estimates are assumed to follow a triangular probability density function.

c. With respect to the choice of the hydrologic model, that model having the type II error which produces the smallest economic effect should be chosen.

d. Identify that combination of hydrologic parameter variability and optimization-model response that produces the greatest effect and make an interval estimation of this parameter using the most unfavorable limit as a design parameter. If possible, reduce the variability of this and other hydrologic parameters by regional analysis.

e. To account for the losses produced by the stochastic nature of streamflow and demands, specify an allowable limit for the water shortages instead of specifying it for the economic losses as a percentage of gross annual benefits.

12. It is recommended that this work be followed by an investigation of the interrelationships existing among the different effects produced by data limitations. These interrelationships should be further investigated and, if possible, formulated. This investigation should also include procedures for the design of a project which, based on the available information, its reliability, and the relationships among these effects,

will enable the planner to make the most out of the information available to him. The joint use of systems analysis and statistical decision theory may be an avenue for this type of research.

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APPENDIX

GUATEMALA PROJECT

APPENDIX

GUATEMALA PROJECT

A.1. Location

The Government of Guatemala is considering the development of land and water resources in an area of about 14,400 square kilometers located in the northern part of the country*, within 90°00' and 91° 30' longitude West, and 15°00' and 16°00' latitude North. Except for its East-central part, this region is underdeveloped and very few settlements exist within it. There is also a colonization project for the region north of the 15°40' parallel, between the 91°15' meridian at the West and the Caribbean Sea at the East. This project (hereafter referred to as the NC Project) includes the building of roads and other infrastructure features and is aimed at decreasing the demographic pressure now existing in the Western highlands (see Fig. 3.1 in the main text).

The main rivers in the region considered by the northern land and water resources project (hereafter referred to as the NLW Project) are the Ixcán (drainage area of approximately 2,000 square kilometers), Xalbal (approximately 1,400 square kilometers), and Chixoy (approximately 11,000 square kilometers), one of the main tributaries to the Usumacinta, which is the largest river in the country and whose drainage area within Guatemala is of about 45,000 square kilometers. All

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* All of the data and information regarding the Guatemala project used as an example in Chapter III and in this Appendix, were obtained from the sources listed alphabetically in section A.7. Where required, an authorization was obtained from the National Economic Planning Council of Guatemala for the use of the data.

of them run towards Mexico and, after contributing to the Usumacinta, into the Gulf of Mexico. Preliminary studies show good possibilities for hydro-power generation and for the obtaining of water for municipal and agricultural purposes by means of a series of dams and reservoirs located at several places along these three rivers.

One of these sites, and the one where perhaps the largest reservoir could be built, may be either about five kilometers downstream of the Chixoy streamgaging station, near El Jocote (drainage area approximately 5762 $Km.^2$), or about some four kilometers further downstream, near El Jute (drainage area approximately 5824 $Km.^2$). Another possibility has also been considered in the vicinity of San Cristóbal (see Figure A.1), although no definite location was available when the data for this study was gathered.

So far, only prefeasibility studies regarding the identification of potential reservoir sites and inventory of resources have been made. Very little economic, hydrologic, and meteorologic information exists for the region. Although good topographic and geologic maps are available, no detailed field studies other than at a reconnaissance level have been carried out to determine the physical and geologic feasibility of the most promising sites.

The site at El Jocote was chosen assuming physical and geologic feasibility for a multi-purpose reservoir (this, however, does not necessarily imply that it is the best one of the three sites mentioned). This reservoir, as a key feature of the NLW Project, was regarded as a sub-system and used to give relevance to the present investigation. Although the system should be considered as a whole in the real world--and there are procedures to analyze complex multi-purpose, multi-basin

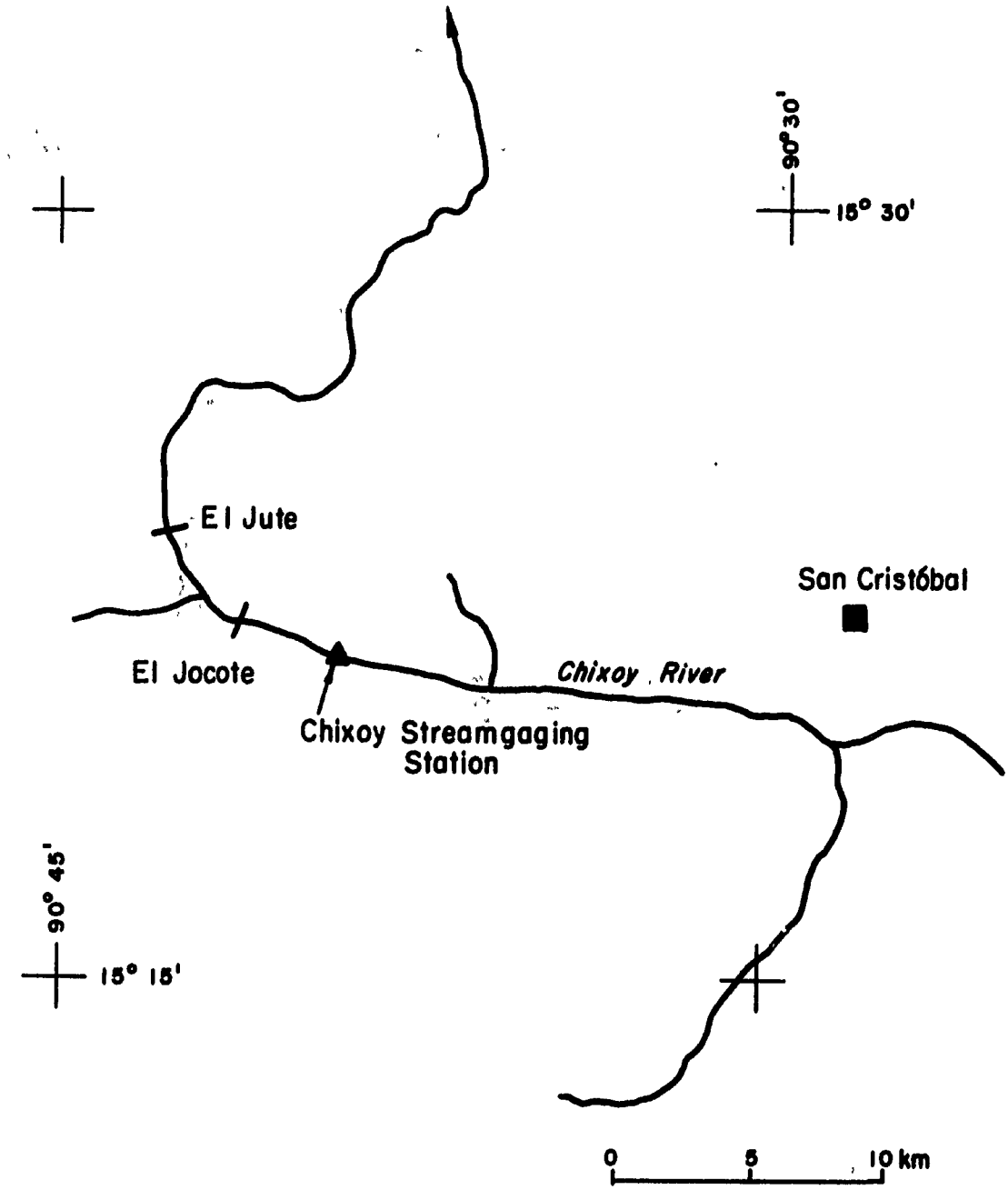


Figure A.1

Chixoy River Reservoir Sites

systems (2)--the isolated analysis of the aforementioned sub-system was deemed adequate for the purposes of this research.

Relevance is not diminished by this fact, since real data under real limitations with as real as possible objectives were used. On the other hand, this reservoir may well be the most important feature in the whole system. More detailed analysis may also indicate that this reservoir should be the first one (or in an extreme case even the only one) that should be built in the region. Moreover, the aim is not planning a water-resources system but to do research within the framework of a real planning example. The research objectives being accomplished, some contributions to the real planning effort are surely to come about.

The site at El Jocote is located at approximately 37 kilometers Southwest of Cobán, the provincial capital of Alta Verapaz, and at approximately 90 kilometers North of Guatemala City, the nucleus of the central power district. Some 50 kilometers to the North of El Jocote, the availability of approximately 42,800 Hectares of land with moderate suitability for irrigation has been estimated (see Figure A.2). This land is grouped in three sections: Chixoy, Canillá, and Icbolay, the names taken from nearby streams. The areas are respectively 18,900, 12,100, and 11,800 Hectares.

The greatest part of this land is covered by dense forests and just a few isolated spots have been cleared where agricultural activity is presently carried on, mostly for corn production on a limited basis. Dominant soil types are Tzejá, Tamahú, Chacalté, Cobán, and Carchá. These soils are adequate for pastures (Tzejá and Tamahú), corn

(Chacalté) and beans (Cobán and Carchá). The approximate areas covered by these soil types and their distribution can be seen in Figure A.3.

Karst conditions*, generally associated with Cretaceous limestones and dolomites are present in the higher parts of the Chixoy River basin. However, they are not evident at the proposed El Jocote dam and reservoir site since the river channel is deeply incised at this location.

A.2 Description

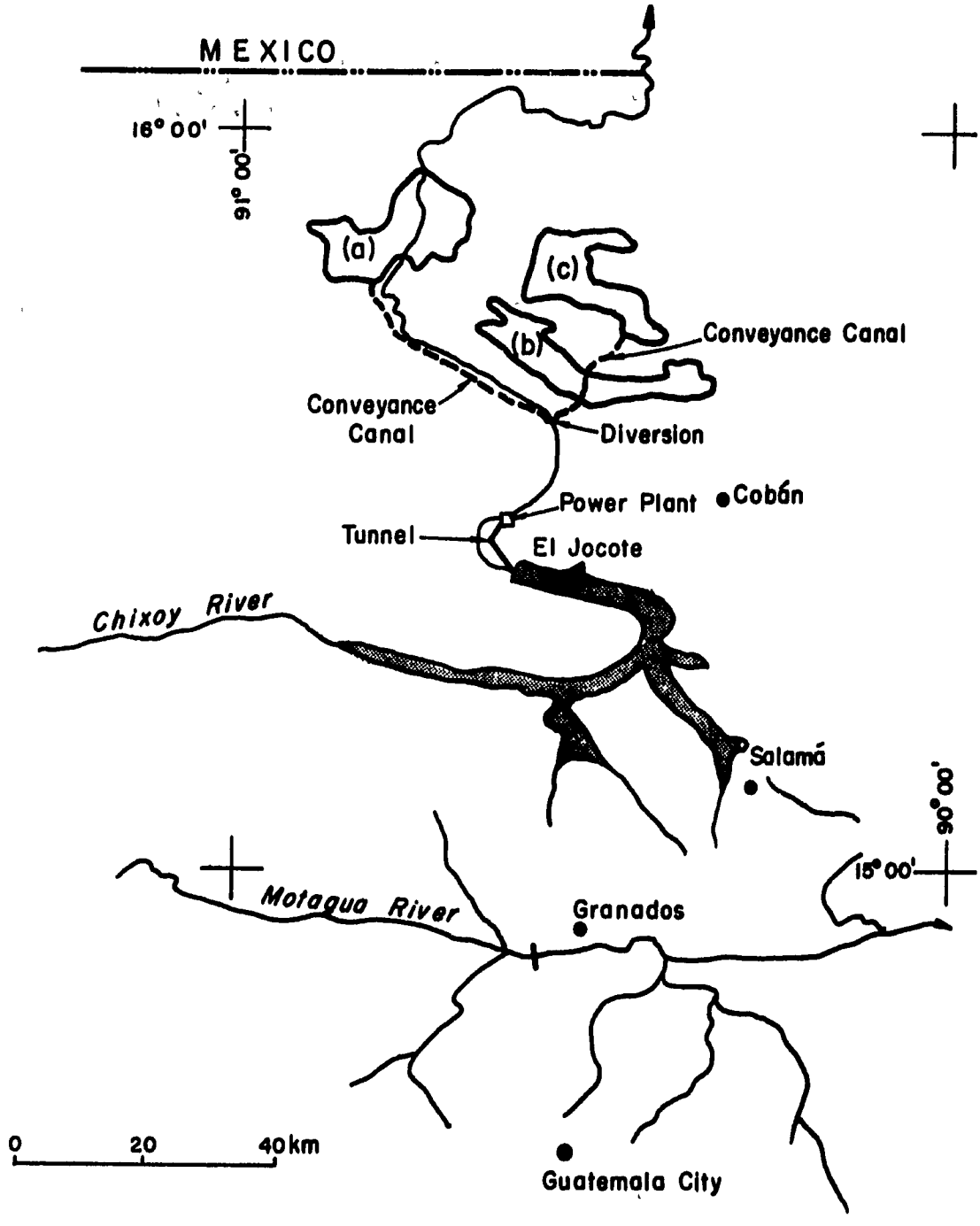
A.2.1. Water Uses

Hydro-Power: From topographic maps it was determined that physical conditions would allow the building of a dam with a maximum height of 240 meters (elevations 560 to 800 meters) and a maximum crest length of about 840 meters in a V shaped canyon, requiring only the relocation of about 10 kilometers of the old road from Huehuetenango to Cobán.

From topographic maps, it was also determined that by a tunnel of 9.75 kilometers an additional 180 meters of fixed head could be obtained. Thus, by assuming a minimum reservoir head of 50 meters, a total of 230 meters of fixed head would be available. Since the mean annual flow of Chixoy River at that point is about 66 cubic meters per second, there are good possibilities for a hydro-power development.

The only drawback could be the distance from the main center of consumption, which is the central power district (the area close to

* Here, Karst is used to describe sinkhole topography and related features, caused by solution of limestones and other carbonate rocks. For a more detailed treatment of the subject and its relation to Hydrology, see reference (58).



Irrigation Sections

(a) Chixoy

(b) Canillá

(c) Icbolay

Figure A.2

Location of El Jocote Project

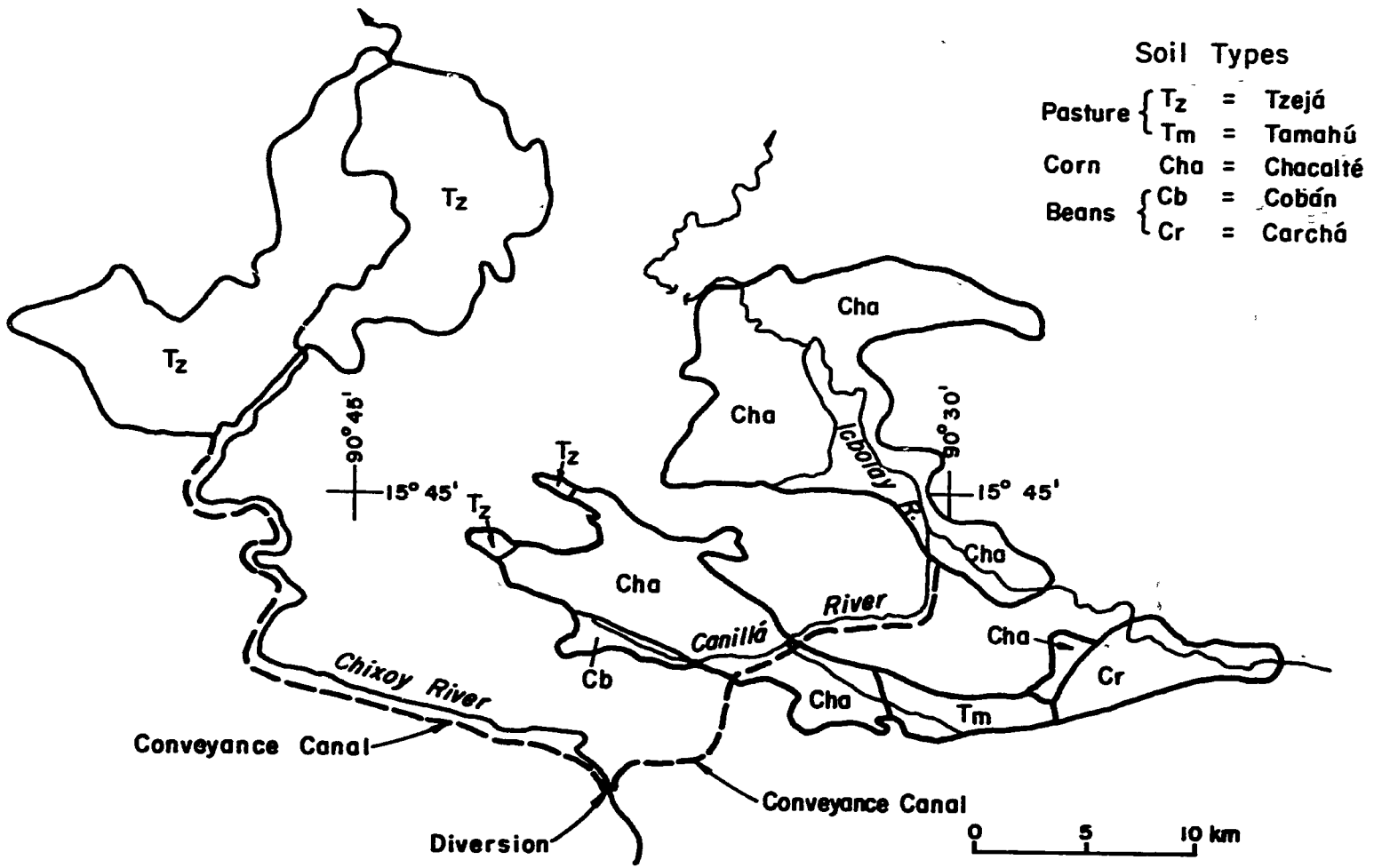


Figure A.3
Irrigation Project

Guatemala City), since the demand in the northern region is too small. However, previous plans for power development and inter-connection of the different power districts included power lines tying Cobán with the central power district. Assuming these plans were going to be carried out, the only additional line to be built would be that from El Jocote to Cobán (a distance of about 37 kilometers).

Irrigation: The development possibilities for irrigated agriculture with water from El Jocote do not look as good as for hydro-power. Negative factors are:

1. The land is not suitable for high-priced crops.
2. Its dense forest cover would increase development costs.
3. The average rainfall in the area is relatively high (see Table A.2).
4. Water from local streams within each of the Chixoy, Canillá and Icbolay sections to irrigate smaller areas could be more economical because of conveyance costs from El Jocote. The use of ground water may also prove to be more economical.

Positive factors are:

1. The NC Project would increase the local market for basic food items such as corn, beans, meat, and dairy products.
2. Shortages of these basic items in the national market could be diminished or avoided.
3. Once the national market has been satisfied, surpluses of these items could then become export items for the Central American market or, in the case of meat, for bigger markets.
4. The needed infrastructure works are contemplated within the NC Project, so market accessibility would not be a problem.

All these considerations warrant a much more detailed analysis than the one made here and involve, of course, many important considerations of political and socio-economic nature which are outside the scope of this work. Under the assumption then that it is desirable to increase the production of the aforementioned items and that it is desirable to develop this land within the NC Project, the physical feasibility of providing irrigation water from El Jocote was investigated based solely upon topographic maps and without the benefit of topographic and geologic field reconnaissance.

From El Jocote, releases for irrigation could be made to the Chixoy River (through the turbines whenever possible) and diverted at a point some 40 kilometers downstream. From this point it would have to be conveyed to the Chixoy section by a canal 40 kilometers long. Another canal of 15 kilometers would take the water from the diversion point to the Canillá section and, if the Icbolay section is included, this canal would continue for 22 more kilometers (see Figure A.3). It is assumed that the geology of the terrain is such as to require these canals to be lined, but does not make them physically infeasible.

The point of diversion is chosen so as to provide the necessary head in order to avoid great pumping costs, since at that point the river goes out of the mountains and into the lowlands. Pumping would probably be needed only for some 2,000 Hectares in the Canillá section. It was just assumed that this scheme is more economic than diverting the water farther downstream and increase the pumping.

<u>Water Supply</u>: A very crude physical feasibility study attempt based on topographic maps was made to explore the possibility of

diverting water from El Jocote reservoir for municipal uses in Guatemala City. The introduction of this scheme involved a trans-basin diversion and involved large pumping lifts. No data had been previously collected to assess the economic feasibility of these features, so it was decided not to include this scheme in the present example.

The only nearby towns for which water-supply might have been considered are Salamá and Cobán, both of which are located at higher altitude than El Jocote. Since the water supply needs of these towns are not as pressing as those of Guatemala City, and because there may be local sources capable of meeting those needs (no survey was made on this aspect), pumping was not believed economically feasible for supplying these towns.

Other Uses: Flood control was included by assigning to it 20 percent of the total storage space. A very rough estimate of possible flood control benefits was made by assuming that they would compensate for the cost of one half of this extra storage. No minimum water or quality requirements to be maintained downstream from the irrigation diversion were considered, and all irrigation returns were assumed downstream of this point or into other streams.

All of the above complexities and considerations even involving matters of national policy, emphasize the need for comprehensive planning and for the use of an approach, such as systems analysis, for designing water resources projects within the reference framework of a national development effort.

A.2.2. The System

The system layout, as considered for this example, is as follows:

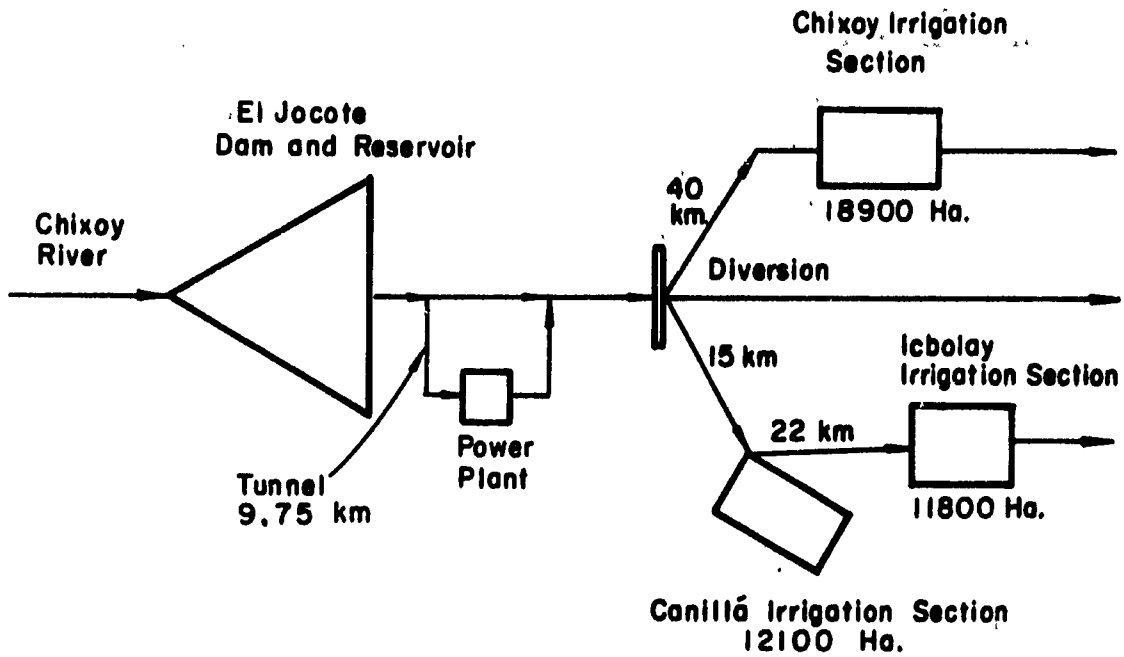


Figure A.4. System Layout of the Example Project

The elevation characteristics of El Jocote site are shown in Figure A.5(c).

A.3. Data

A.3.1. Geophysical

Reservoir Site: Based on topographical maps Scale 1 to 50,000, volume-elevation and area-elevation curves were drawn. The data used is on Table A.1. Figure A.5 shows the aforementioned curves.

Hydrometeorological Data: Except for the streamgaging station Puente Chixoy, no hydrometeorological records are available for the reservoir site or the land to be irrigated. Data from the closest station in the closest similar region was used for monthly precipitation, maximum and minimum monthly temperature and mean monthly evaporation.

TABLE A.1

Area-Elevation and Volume-Elevation Data for El Jocote Reservoir

Elevation in Meters (Datum 560 m)	Surface Area in Million Square Meters	Accumulated Volume	
		Million Cubic Meters	Thousand Acre-Feet
0	0	0	0
20	1.875	39.600	32.25
80	6.700	296.600	242.00
120	11.596	658.600	536.00
180	24.120	1728.600	1410.00
220	39.650	3008.600	2440.00

Mean monthly precipitation for the irrigation area was obtained from an available isohyetal map and the monthly percentage of annual daylight hours was estimated from data reported for Honduras. The data used is summarized in Table A.2 and the location of the stations is shown in Figure A.6. A very rough estimation of floods for spillway design was made from the enveloping curve of Figure A.7, based on the Craeger's equation with a C coefficient of 110, obtaining a value of about 16,800 cubic meters per second.

Figure A.5 (a)

Volume-Elevation Curve for El Jocote Reservoir

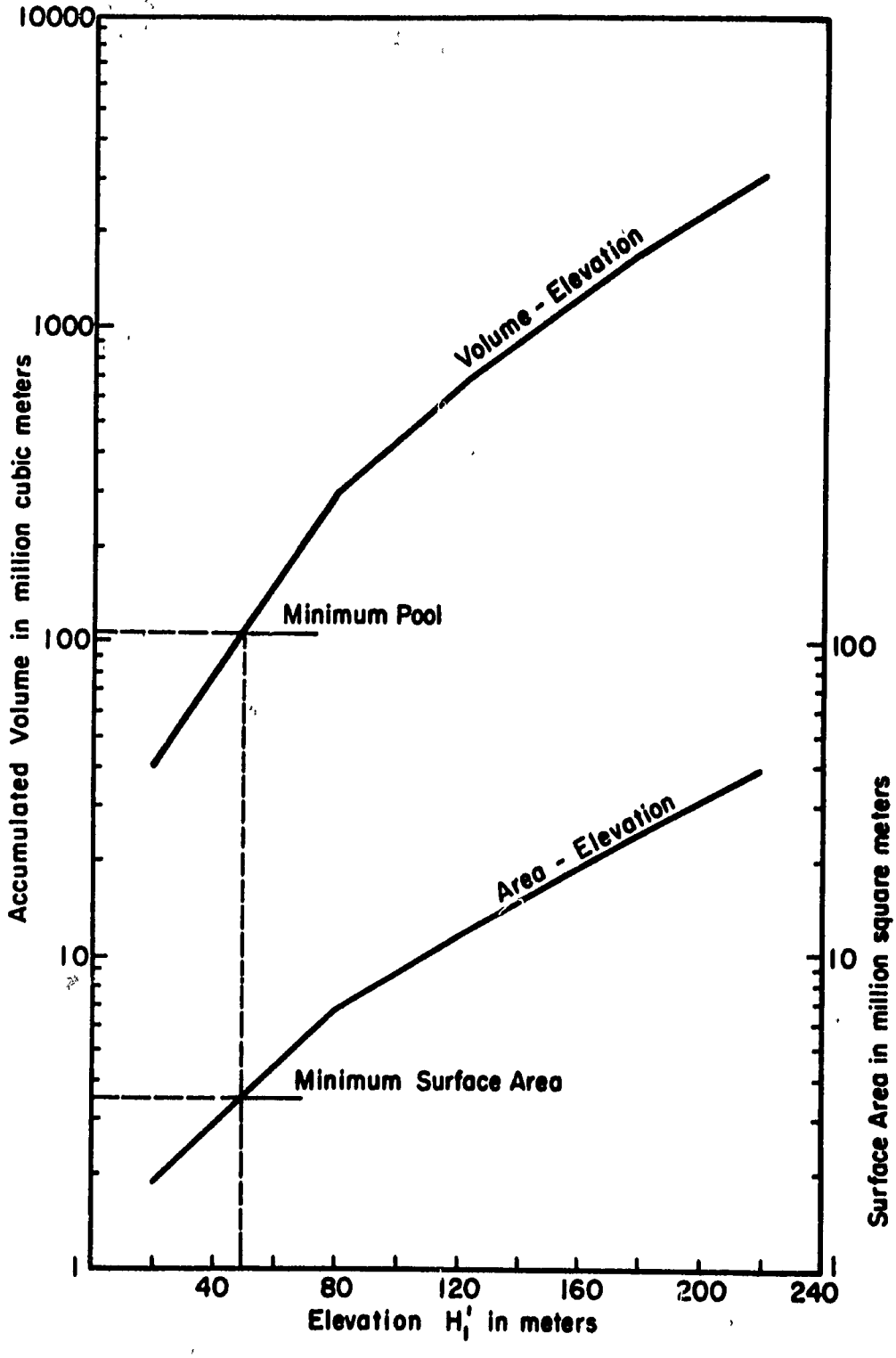
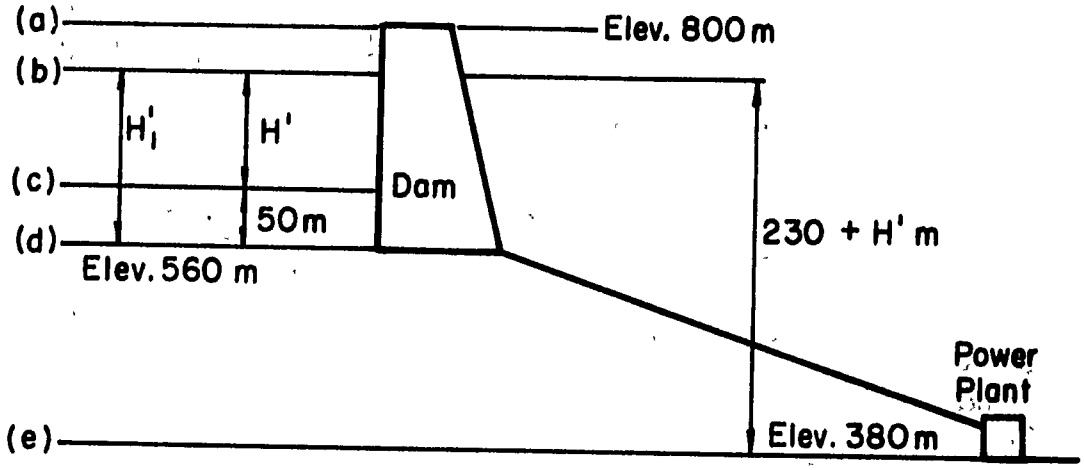


Figure A.5 (b)

Area-Elevation Curve for El Jocote Reservoir



(a) Maximum flood control pool elevation
(b) Maximum conservation pool elevation
(c) Minimum pool elevation
(d) Elevation at dam site
(e) Tailwater elevation

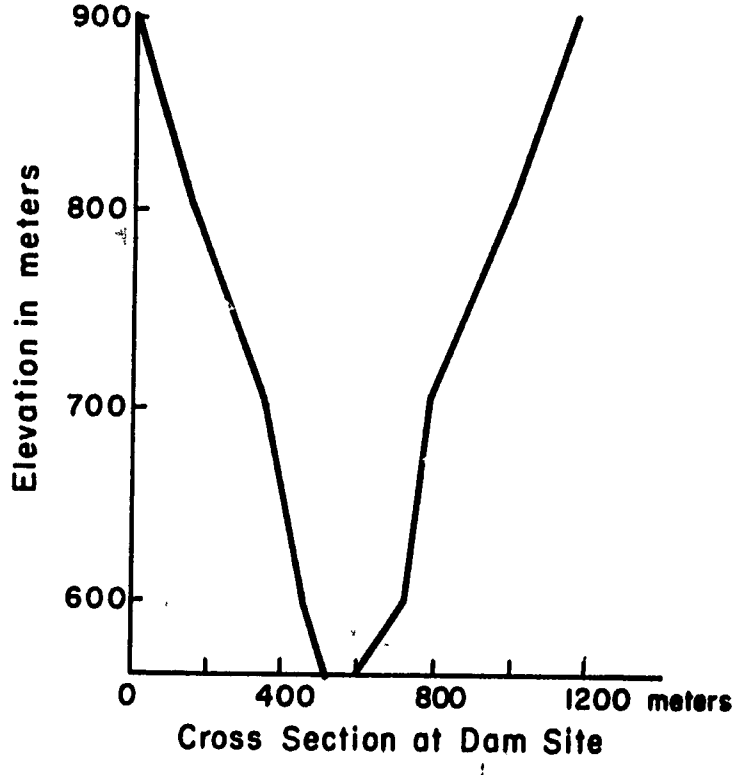


Figure A.5 (c)

Characteristics of El Jocote Dam Site

A.3.2. Economic

Cost and Benefit Curves: Cost and benefit curves obtained for the following items are in Figure A.8 to A.13:

1. Irrigation:
   a. Capital cost of diversion works.
   b. Capital cost of irrigation works from the secondaries on, including land preparation (gravity).
   c. Operation and maintenance costs for the irrigation project.
   d. Net crop benefits (benefits less production costs, irrigation costs not included) for pasture, corn, and beans.
2. Hydro-Power:
   a. Capital cost of power plants, including penstocks.
   b. Operation and maintenance costs of power plants.
3. Reservoir:
   a. Capital cost of reservoirs.
   b. Operation and maintenance costs of reservoirs.

To obtain these curves, a rather laborious procedure had to be followed. First; from a series of project reports and proposals where cost and benefit data were given, a common denominator had to be found to which costs and benefits could be associated in each case. Since cost and benefit data are included in a rather dissimilar way in these reports, the criterion followed was that of relating these figures to parameters that were explicitly given in these reports. For example, the capital cost for diversion works was related to Lh, L being the crest length and h the maximum height of the diversion dam.

TABLE A.2

Hydrometeorological Data

A.2.1. Monthly Discharge in Cubic Meters per Second (20)(24)*

Station: 14.15.1.H Puente Chixoy INDE Drainage Area: 5727 Km.^{2}
Latitude: 15°21'30" Longitude: 90°39'30" Elevation: 600 Meters

Water Year	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
1962-1963	27.4	69.7	90.4	65.8	152.7	92.2	43.5	28.0	21.8	18.7	17.4	16.9
1963-1964	15.5	49.7	77.8	55.6	72.6	69.7	45.4	29.3	22.9	18.6	15.0	17.1
1964-1965	15.4	44.8	79.3	64.7	110.7	104.9	41.1	36.2	26.4	19.6	14.9	14.4
1965-1966	16.1	57.2	50.4	55.5	100.0	125.4	65.3	35.1	26.2	20.4	18.2	26.0
1966-1967	24.8	166.2	133.4	69.2	130.6	173.8	49.5	38.3	21.0	27.8	25.8	26.3
1967-1968	14.6	98.8	96.0	69.6	125.6	287.1	52.2	33.0	25.5	21.1	15.6	15.0
1968-1969	35.7	167.5	83.4	56.0	216.2	210.0	74.3	42.1	30.2	28.1	20.5	19.3
1969-1970	34.7	140.1	203.2	255.9	323.7	161.3	74.5	55.0	37.1	30.3	28.9	21.9

* For all the tables in this Appendix, the numerals in parenthesis refer to corresponding items in the source list presented in section A.7.

TABLE A.2 (Continued)

A.2.2. Monthly Precipitation in Millimeters (12)(31)

Station: 1.1.5 Cubilgüitz

Latitude: 15°40' Longitude: 90°26' Elevation: 519 Meters

Water Year	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
1956-1957	352.0	735.5	511.0	356.0	693.0	582.0	380.0	444.0	202.0	291.0	76.0	39.0
1957-1958	166.0	495.0	635.0	391.0	868.0	400.0	165.0	378.2	254.0	61.0	324.0	68.0
1958-1959	588.0	958.0	876.0	271.0	481.0	415.0	488.0	519.0	248.0	129.0	253.0	450.0
1959-1960	352.0	457.0	287.0	311.0	380.0	590.0	461.0	171.5	296.0	72.0	137.5	144.4
1960-1961	399.0	667.0	351.0	653.0	1064.5	565.0	295.0	228.0	479.0	245.0	244.5	149.5
1961-1962	213.0	394.0	418.0	613.0	383.0	725.0	307.0	121.0	266.0	81.0	320.0	175.0
1962-1963	176.0	444.0	449.0	466.0	590.0	430.0	201.0	108.0	158.0	78.0	114.0	19.0
1963-1964	66.0	357.0	366.0	347.0	686.0	634.0	357.0	272.0	150.0	100.0	163.0	36.0
1964-1965	238.0	590.0	623.0	465.0	320.0	311.0	484.0	656.0	298.0	125.0	30.0	20.0
1965-1966	79.0	572.0	401.0	443.0	815.0	853.0	416.0	458.0	438.0	249.0	533.0	217.0
1966-1967	423.0	520.0	505.0	330.0	691.0	679.0	405.0	175.0	326.0	163.0	134.0	266.0
1967-1968	26.0	393.0	627.0	667.0	419.0	851.0	490.0	222.0	264.0	188.0	198.0	26.0
1968-1969	541.0	509.0	509.0	354.0	630.0	512.0	443.0	346.0	229.0	243.0	334.0	103.0
1969-1970	309.0	634.0	509.0	539.0	613.0	640.0	655.0	105.0	253.0	149.0	47.0	147.0

TABLE A.2 (Continued)

A.2.3. Mean Monthly Precipitation for the Irrigation Project Area in Millimeters (1)

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
200.0	170.0	40.0	125.0	225.0	450.0	500.0	400.0	550.0	500.0	360.0	500.0

Effective precipitation: 60 percent (1)
Total irrigation losses: 60 percent (1)

A.2.4. Monthly Average Temperature in °C: $(T_{max} + T_{min})/2$ (31)

Station: 1.3.8 Sebol (4 year averages)
Latitude: 15°48' Longitude: 89°56' Elevation: 140 Meters

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
22.3	22.6	24.8	26.8	26.6	26.9	26.0	26.4	26.2	25.6	24.1	21.9

A.2.5. Mean Monthly Pan Evaporation in Millimeters (20)

Station: 2.6.4 San Jeronimo Rh (2 year averages)
Latitude: 15°05' Longitude: 90°16' Elevation: 979 Meters

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
98	104	139	143	132	108	102	91	76	71	76	81

A.2.6. Monthly Percentage of Annual Daylight Hours (35)

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
7.8	8.0	8.3	8.6	8.8	8.9	8.9	8.7	8.4	8.1	7.8	7.7

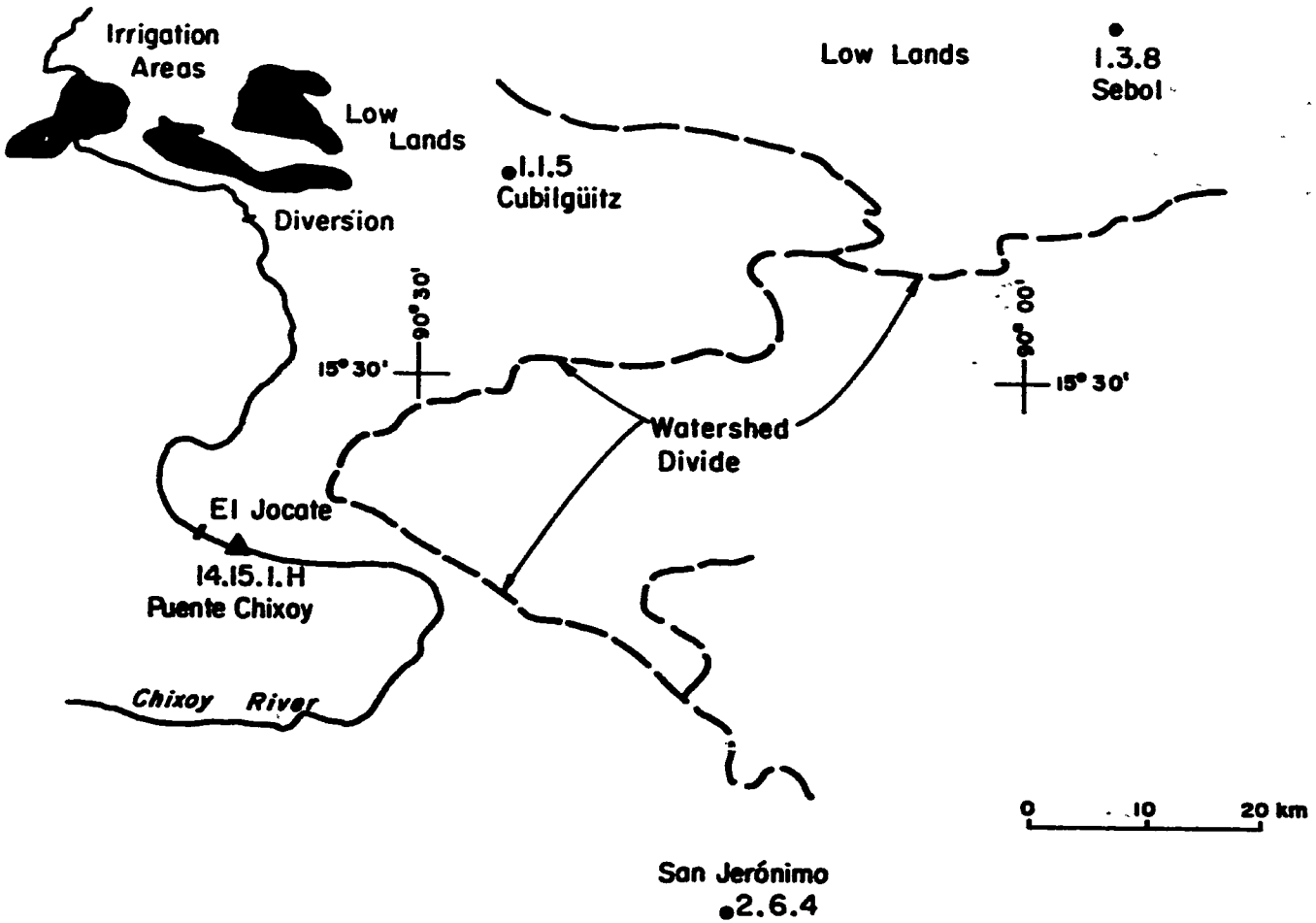


Figure A.6

Location of Hydrometeorological Stations

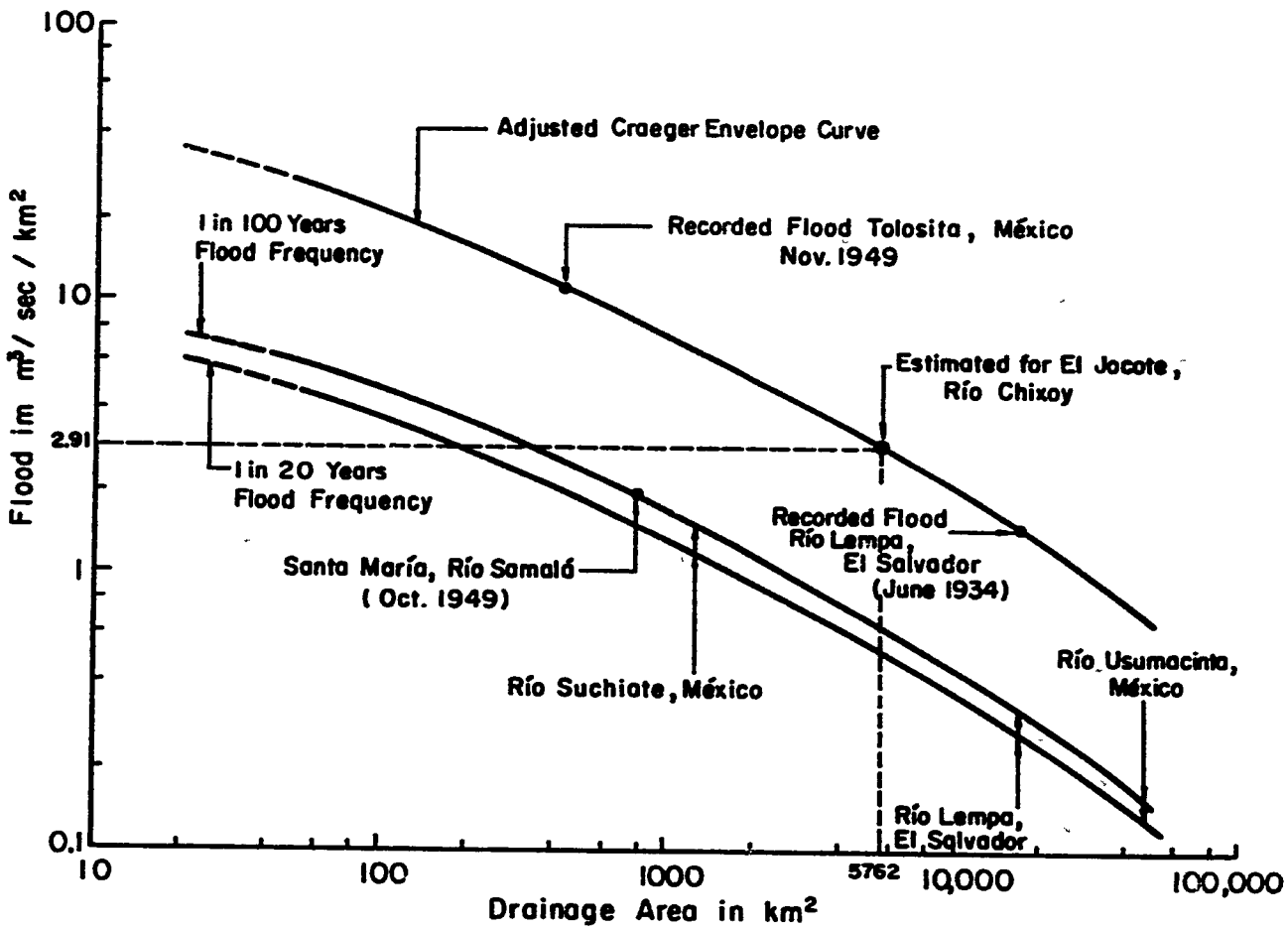


Figure A.7

Craeger Envelope Curve with Coefficient C = 110
From Source (1) of Section A.7

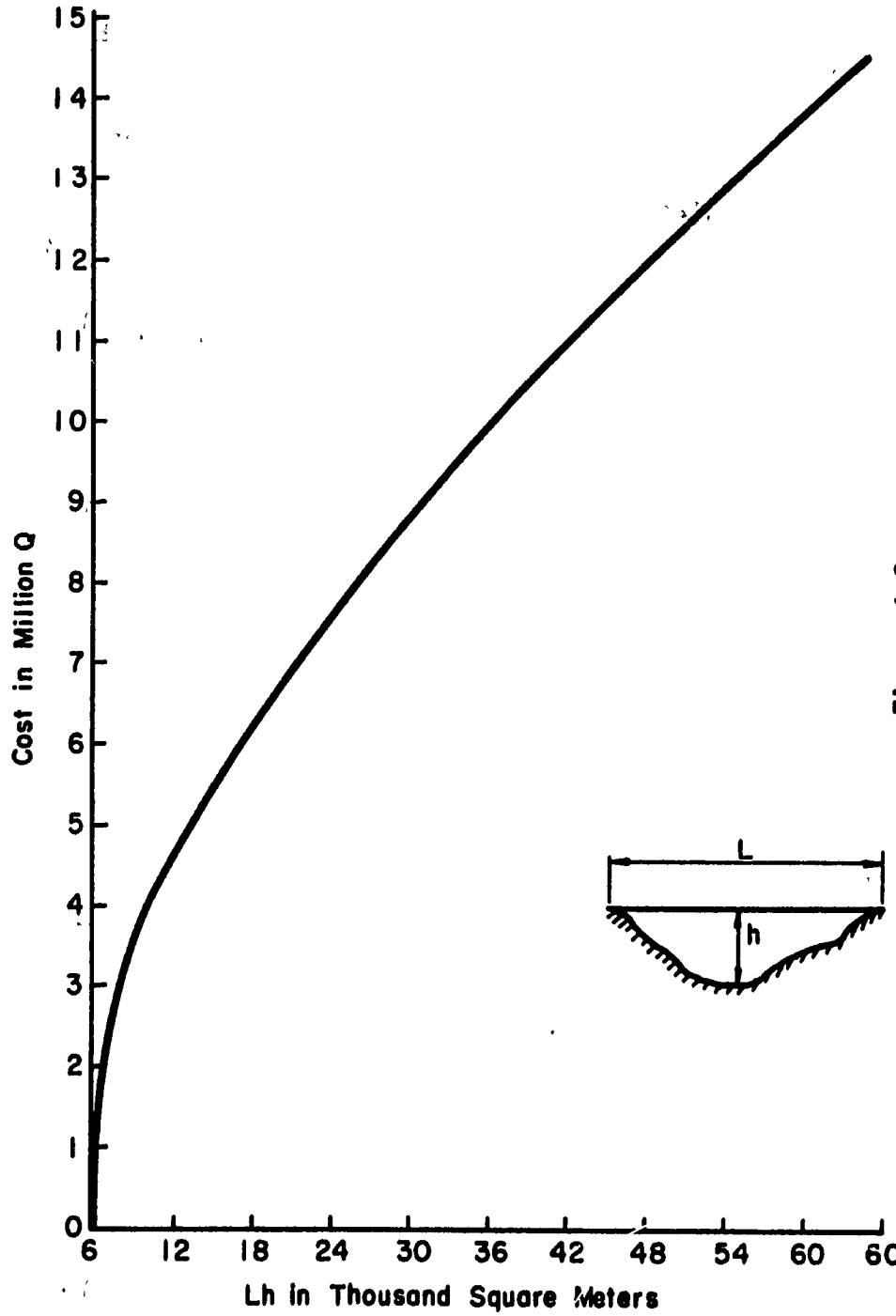
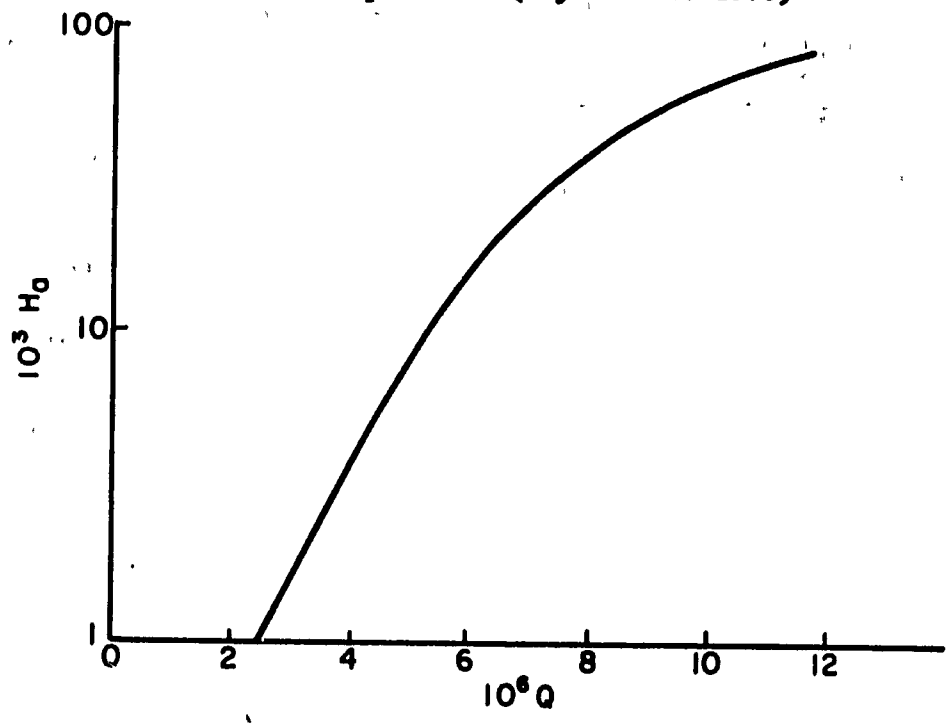


Figure A.8

Capital Cost of Diversion Works (Adjusted to 1970)

Figure A.9

Capital Cost of Irrigation System Including Land Preparation (Adjusted to 1970)



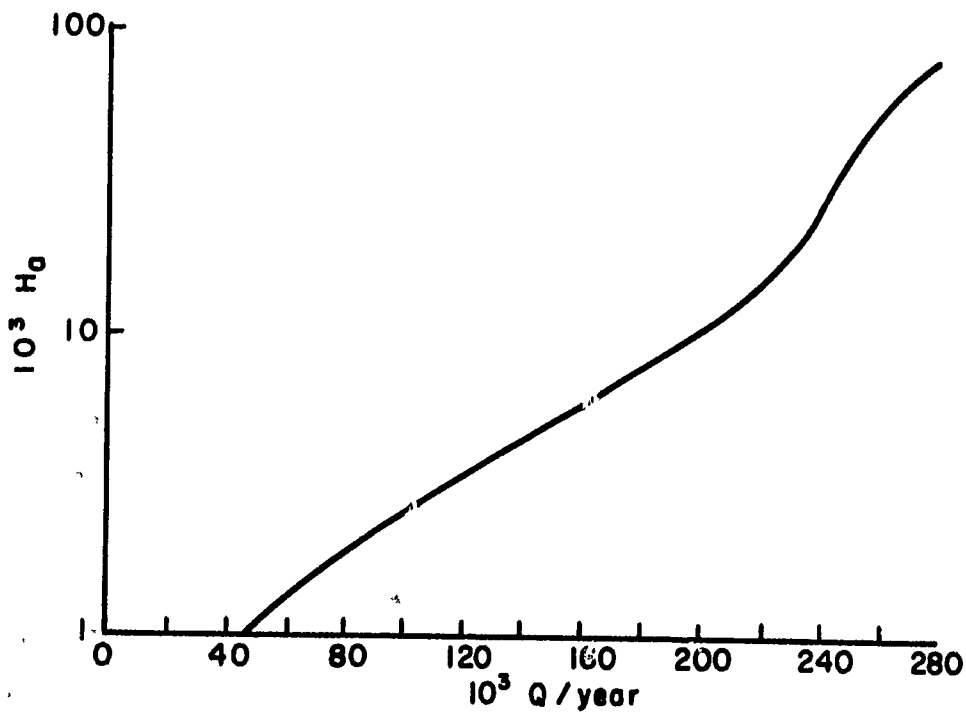


Figure A.10

Annual Operation and Maintenance Costs for Irrigation (Adjusted to 1970)

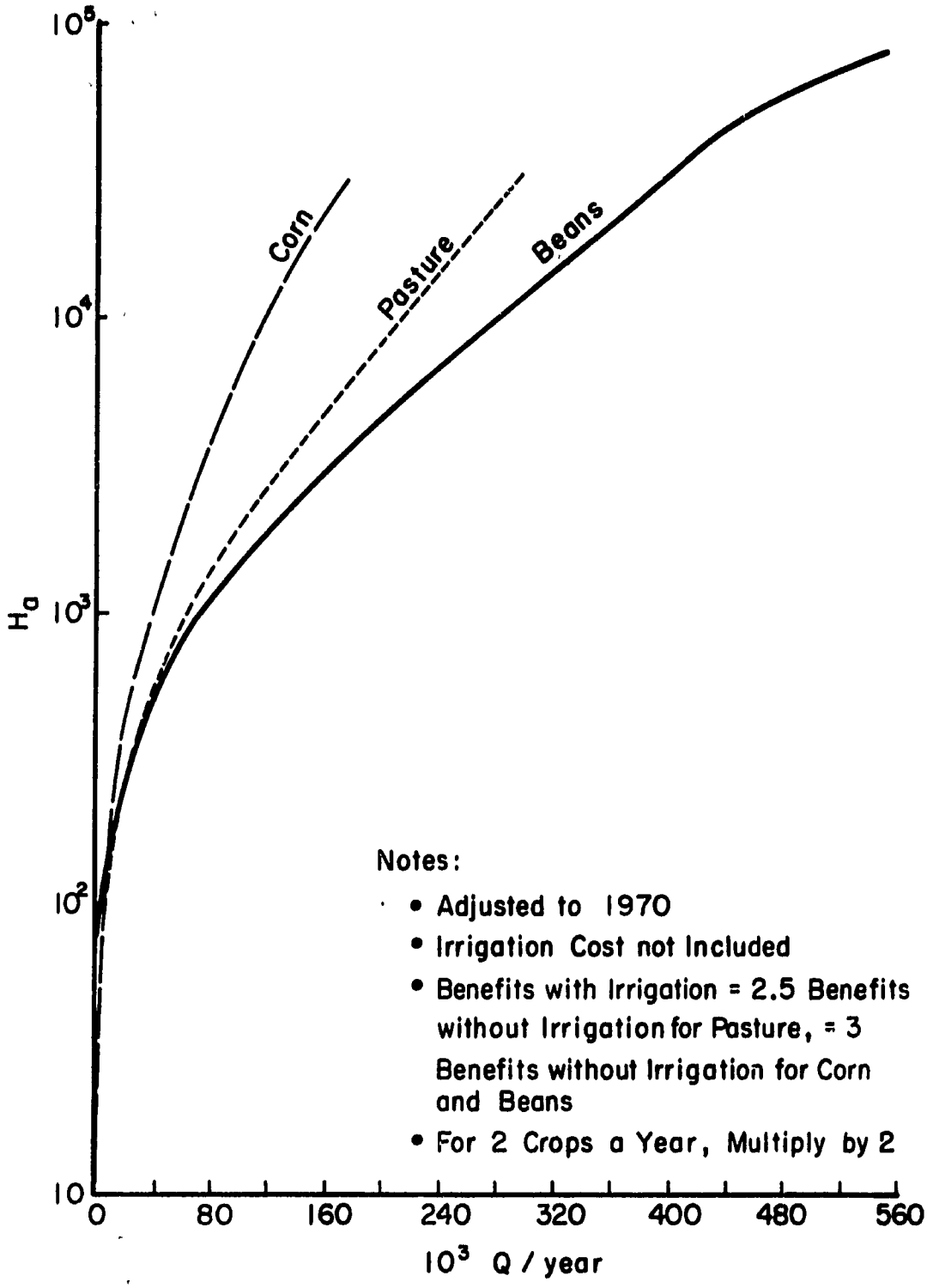


Figure A.11

Crop Annual Net Return Increase

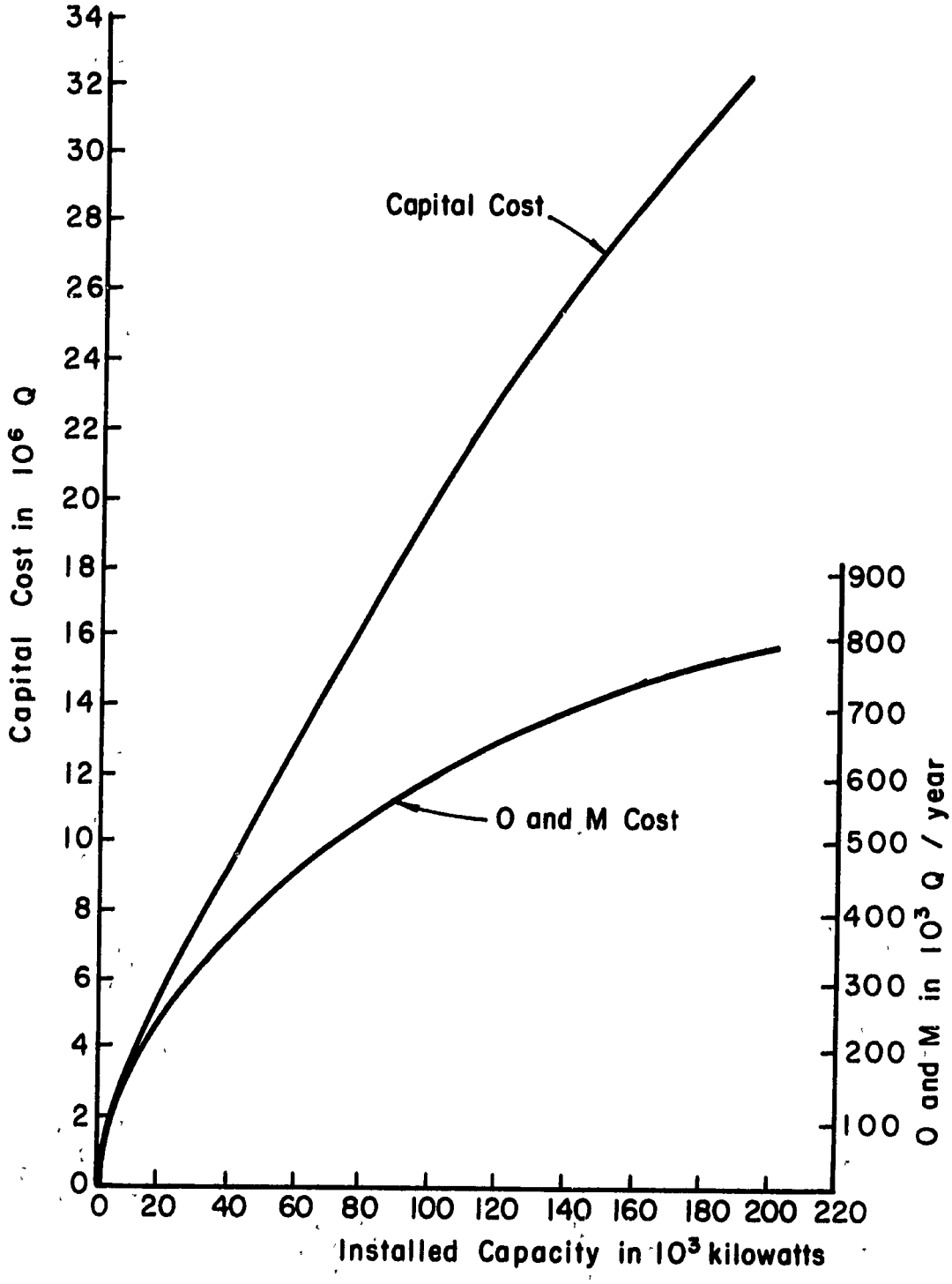


Figure A.12

Capital and Operation and Maintenance Costs of Power Plants

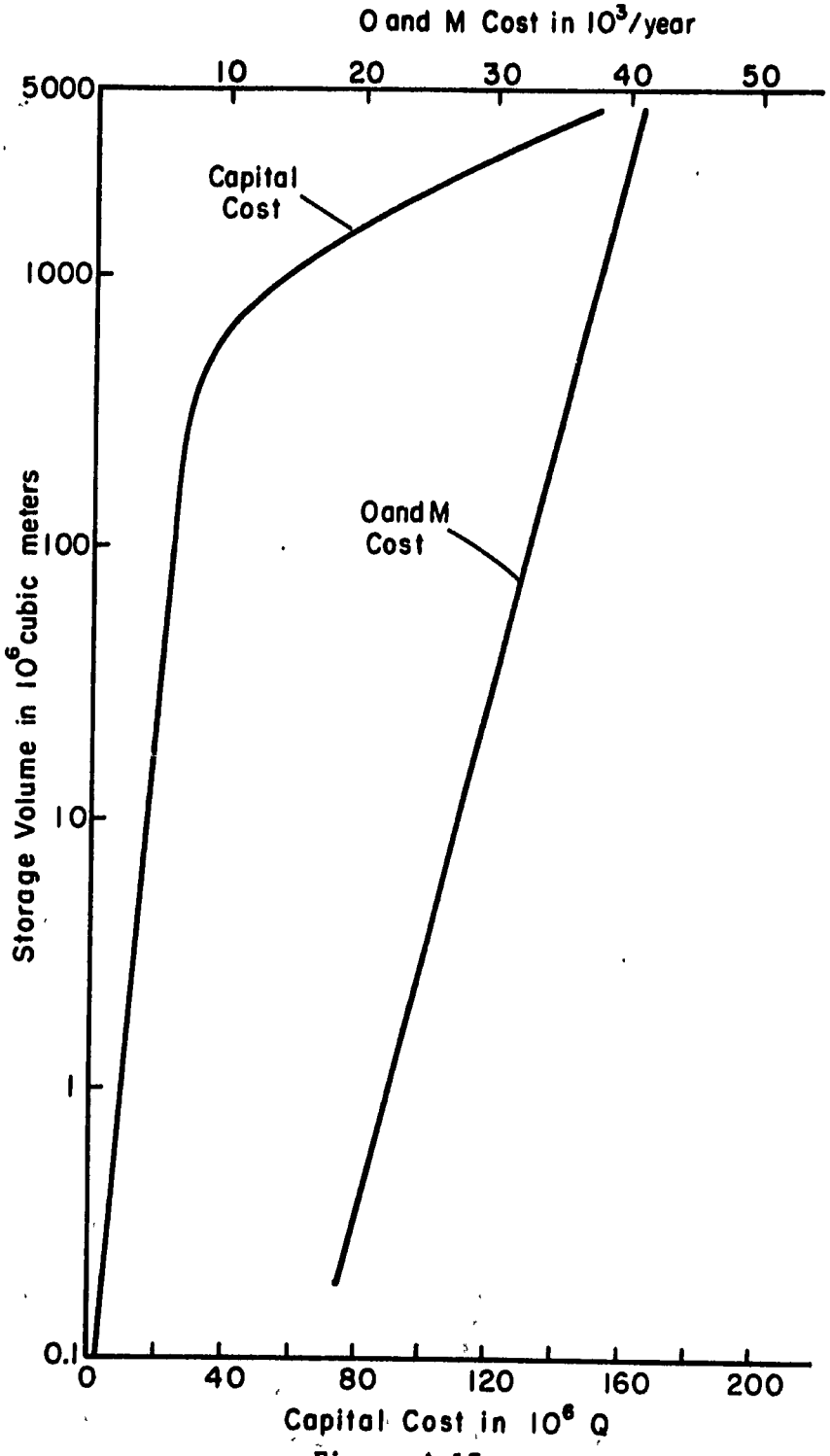


Figure A.13

Capital and Operation and Maintenance Costs of Storage Reservoirs (Adjusted to 1970)

Conveyance costs, assumed constant at Q 17,500/Km., were related to the length of the canal only and no capacity considerations were made*. Costs for irrigation works, operation and maintenance costs, and crop net benefits were related to the net irrigated area.

A factor of 12 percent for construction equipment and installations, and a factor of 10 percent for contingencies were added to all capital costs whenever these costs did not include them. Capital costs of power plants and reservoirs include also the interest during construction, computed by assuming five years at 12 percent annually.

Since the reports are from different years, all costs were standardized to 1970 by a standardization factor of 5 percent per annum. For the net crop benefits, a 2 percent factor was used and the assumption was made that the benefits with irrigation are 2.5 times those that would be obtained without irrigation for perennials (pasture) and three times for twice-a-year crops (corn and beans).

Since most of these reports referred to small scale projects, the upper portion of the curves was estimated, whenever possible, with the aid of cost and benefit figures given for the United States in references (40), (44), and (59), making the necessary adjustments to make them compatible to the Guatemala costs and benefits as described in the above paragraph. For the case of capital costs for large reservoirs, the estimation of the upper portion of the curves was also made with the aid of Figure A.14 taken from Sorensen and Jackson (60), including also the necessary adjustments.

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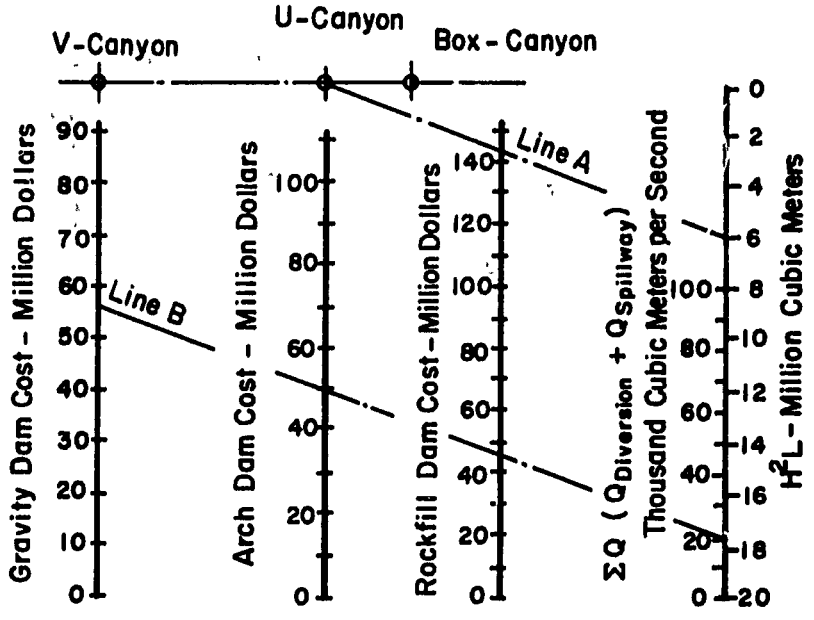
* Q is the symbol for Quetzal, the monetary unit of Guatemala (1 Quetzal = 1 U.S. Dollar).



H = Estimate Structural Height of Dam

L = Crest Length Abutment to Abutment

Line A - From H^2L to Canyon Shape

Line B - Parallel to Line A - from ΣQ to Construction Cost

(Probable accuracy ± 25 %)

Figure A.14*

Nomogram for Preliminary Cost Appraisal of Dams Over 50 Meters High

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* From Sorensen and Jackson reference (60) in the List of References.

Operation and maintenance costs for pumping were estimated to be Q 6.00 per Hectare per year, capital costs for pumping were estimated as Q 200 per Hectare, tunnel construction costs in the area as Q 1,290,000 per kilometer, transmission line costs as Q 31,800 per kilometer, and conveyance capital costs as Q 175,000 per kilometer. All costs are on a 1970 basis.

Losses: The average annual shortage ratios (see section about the final form of the objective function in Chapter VI) that can be tolerated by crops are quite variable, depending upon factors such as the type of crop, soil moisture conditions, growth stage, and flexibility of the irrigation operations. No data was available for Guatemala from which to develop an annual loss-annual shortage ratio curve to estimate the coefficient b of Equation (6.1), for agricultural areas. The value of 9.5 given in reference (46) was thus arbitrarily adopted for no reason at all other than because the curve shown in this figure is supposed to represent a typical reasonable relationship for agricultural areas.

For hydro-power the situation gets more complex. In developed countries, contracts for power are subscribed based on a 100 percent availability for a given price for firm power, so that no shortages at all are allowed. A power system, however, may comply with this requirement by turning to the next cheapest source available at other systems to supply--at a cost--the deficit of small and infrequent shortages that may be experienced. The power system insures itself against severe shortages by assigning a very high penalty to shortages above a certain limit, so that alternatives that would produce these shortages are automatically eliminated in the economic analysis by

a loss function. This loss function will also evaluate the cost of shortages below that limit by assigning the cost of buying from the cheapest alternative as a penalty.

In small developing countries, however, the case may well be that the project under consideration is going to be the major source of energy for the system and that there are no other systems from which to buy the energy required to supply these small deficits. Furthermore, the energy may be scarce in the country and the users have to buy whatever energy is available. Under these conditions it should not be surprising that contracts for power are structured in this fashion, with no price distinctions made for firm power. This circumstance, however, may not prevail in a given country forever, and later on contracts may be renegotiated.

The construction of a power loss function then gets complicated because there is no cost of buying from an alternative source that can be assigned as a penalty, since the power system itself will not lose anything by these shortages. Consumers, however, do lose and although it may be possible to approximately evaluate these losses (in the case of industry for example), no data for such a task were available for Guatemala.

When contracts are structured in the manner just described, it will be unfair not to give the users an idea of the uncertainty associated with a given power supply, uncertainty that is produced by the stochastic nature of both supply and demand. This is another advantage of the systems approach and an objective function such as that of Equation (6.5).

Based on the considerations previously made, no discontinuity was assumed for the power loss function but, to limit the allowable shortages, a quadratic loss function similar to the one assumed for irrigation was adopted. Recognizing that the consequences of power shortages may be more serious than irrigation shortages, a b coefficient of 20 (annual loss/annual shortage) was arbitrarily assumed for hydropower.

Power Benefits: The estimation of benefits from hydro-power in developing countries may also get complicated. In developed countries, these benefits are estimated in terms of the cost of the cheapest alternative available (other than hydro), under the premise that if the project under consideration is not built, the next cheapest alternative will provide the energy and if it is built, these foregone costs will be the benefits of the project. An implicit assumption is that an adequate balance exists between the different sources so that prices are more or less stabilized and will not be influenced by the new project.

The benefits from hydropower are expressed by two components (14), (40): a value for the kilowatts of power supplied, and a value for the kilowatts-hour of energy delivered. The first component represents the fixed costs of the alternative source of power, and the second represents the variable costs of this alternative (mainly fuel costs). In preliminary planning stages such as this, these two parts are expressed in a single average value for kilowatt-hours by taking the value of the power component over the average hours per month that this power is demanded, and then adding this value to the energy value.

In developing countries, however, because of an imbalance in the sources being used (among other reasons) the existing average energy prices may be very high and one of the objectives for building a hydroelectric project may be precisely to lower these prices*. As will be shown in the next section, the price to be used depends upon the size of the project to be built and upon economic-policy considerations of the planning agency, so that no arbitrary price may be assumed. A price of Q 0.018 per kilowatt-hour was finally selected for reasons which will be explained in the next section.

A.4. Conventional Economic Analysis

For this analysis, it was assumed that project construction would be from 1975 to 1979 and that project operations would begin in 1980.

A.4.1. Demands

Irrigation: Average monthly diversion requirements were estimated using the methods outlined in Chapter II, and the data of Table A.2, assuming the following crop pattern (Table A.3).

This gives a total net area of 24,700 Ha (the Icbolay section was not considered at this stage), and monthly diversion requirements as indicated in Table A.4.

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* The main reason being to encourage the development of the industrial sector. Whether it can be obtained or not depends on each particular case, since the price of energy is only one of the many factors which can encourage or discourage the establishment of new industries. Whether it can decrease the cost of manufactured goods is also a fact that cannot be established a priori and should be examined with more detail in each case. These analyses fall within the realm of national policy-making.

TABLE A.3

Crop Pattern in the Project Area*

Section	Net Area ** Ha.	Soil Type	Crop	Type	Growing Period
Chixoy	15,000	Tzejá	pasture	perennial	starting May 15
Canillá	1,200	Tamahú Tzejá	pasture	perennial	starting May 15
	5,700	Chacalté	corn	two-crop	approx. 136 days May 15-Oct. 1 Nov.15 April 1
	800	Cobán	beans	two-crop	approx. 136 days June 1-Oct. 15 Dec. 1-April 15
	2,000 (pumping)	Carchá	beans	two-crop	approx. 136 days June 1-Oct. 15 Dec. 1-April 15

** Net area is 80 percent of gross area. It is assumed that 20 percent of gross area is used by canals, roads, etc.

TABLE A.4

Monthly Irrigation Diversion Requirements

Month	Diversion requirements in million cubic meters
Jan.	2.10
Feb.	15.10
Mar.	76.50
Apr.	19.20

* These are best estimates obtained by the author based on the available information, without the benefit of an Agronomist consultant.

Hydro-Power: Two projections of annual energy demands were made: by the rate of aggregate increase and by per capita consumptions. For the first one and using estimates of the National Development Plan that demand will increase at an annual rate of 12.6 percent, an estimated demand of 1,960 $X10^6$ kilowatts-hour was obtained for 1980, based on the 1967 demand. However, the historical demands have been restricted by the means of supply. To avoid this, the second estimate was made using the following index: I = Energy per capita (kw-h/year)/Annual per capita Gross National Product. The values shown in Table A.5 are from statistics reported by the Agency for International Development (AID):

TABLE A.5

Selected Energy Indexes for Latin America

Country	I
19 Latin American Republics	1.04
Costa Rica	1.09
Central America (including Panamá)	0.62
Guatemala	0.38
Central America (including Panamá but excluding Guatemala)	0.72
Central America (excluding Guatemala)	0.69

Using I = 0.72, and a desired per capita Gross National Product (GNP) of Q 500 (present per capita GNP is about Q 346 and the goal for 1980 expressed in the Development Plan is Q 500), a projected

figure of 360 kw-h/year per capita was obtained for 1980. With this figure and a projected population of 7.25 million, a projected annual energy demand of 2600 $X10^6$ kilowatt-hours was obtained for 1980. According to present plans the estimated supply for 1980, not including the NLW Project, is 1600 $X10^6$ kw-h so that a net unsatisfied demand of 1000 $X10^6$ kw-h would exist according to these estimates.

The NLW Project as a whole may or may not be able to satisfy this demand. Assuming that it could, the questions are how much of this demand would El Jocote reservoir be able to meet, what the reservoir size would be, and what capacity could be installed. To answer this, the water supply and the irrigation demands must also be taken into consideration.

First, the average monthly percentage of annual energy and the average monthly load factor were obtained from historical records. Then, a mass diagram for monthly flow volumes was constructed and by trying several sequences of monthly energy requirements (corresponding to several assumed annual energy demands) combined with the irrigation requirements, the annual energy demand to be satisfied by the project was estimated to be 828 $X10^6$ kw-h.

The necessary storage was 850 $X10^6 m^3$. Adding 108 $X10^6 m^3$ for minimum storage (see Figure A.5) gives 958 $X10^6 m^3$ and, dividing by 0.80, a total of 1195 $X10^6 m^3$ is obtained, 20 percent of which is for flood control. Figure A.5(b) gives an elevation of 142 mts. for 958 $X10^6 m^3$ and from Figure A.5 (c) it is seen that the average head can be computed as 230+H'(1/2) = 230+(142-50)/2 = 276 meters. Using the above estimates, Equation (2.28) gives an installed capacity of 175,000 kw.

The diversion requirements for hydro-power are as follows:

TABLE A.6

Monthly Hydro-Power Diversion Requirements

Month	% of annual energy	Monthly energy in million Kw-h	Monthly load factor	Requirements: Flow in m^3/sec.*	Requirements: Vol. in million cubic meters
Jan.	8.28	68.4	0.60	45.2	119.0
Feb.	7.80	64.5	0.57	42.5	112.0
Mar.	8.36	69.0	0.60	45.5	120.0
Apr.	7.71	64.0	0.56	42.0	110.5
May	8.45	70.0	0.62	46.3	122.0
June	8.17	67.5	0.61	44.5	117.0
July	8.35	69.0	0.62	45.5	120.0
Aug.	8.43	69.8	0.61	46.1	121.8
Sept.	8.21	68.0	0.59	44.7	118.0
Oct.	8.63	71.5	0.61	47.0	124.0
Nov.	8.47	70.0	0.58	46.3	122.0
Dec.	9.13	75.5	0.59	49.9	131.5

* Obtained using Equation (2.27) with an average gross head of 276 m , and assuming an 85 percent efficiency of turbines and generators and a 90 percent efficiency in head. Using Equation (2.28) the capacity to be installed is 175,000 Kw.

A.4.2. Benefit-Cost Analysis

Costs: The computation of costs was made based on the sizes of the different elements of the project and on the cost curves given

in this Appendix. A summary of these costs is as follows:

Element Sizes:

Reservoir*: 1060 $X10^6$ cubic meters
Hydro plant: 175,000 Kw
Irrigated area: 24,700 Ha (including 2,000 Ha involving pumping)
Conveyance canals: 55 Km
Tunnels: 9.75 Km
Transmission lines: 37 Km
Diversion works: L = 250 m; h = 25 m

Capital Cost:

Reservoir	Q 58,000,000
Hydro plant	30,000,000
Tunnel	12,550,000
Transmission	1,180,000
Diversion	5,450,000
Conveyance	9,620,000
Irrigation network	6,800,000
Pumps	400,000
	Q 124,000,000

Annual Costs:

Power plant	Q 750,000
Reservoir	38,000
Irrigation	240,000
Pumping	12,000
	Q 1040,000

Benefits: Benefits from irrigation are obtained from Figure A.11. To obtain the benefits from the energy, however, several considerations must be made. As it has been previously stated, energy prices in Guatemala are high. Their structure is as follows:

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* The real size was 1195 $X10^6 m^3$ including the extra storage for flood control. To account also for possible benefits from flood control, only 10 percent instead of the 20 percent of total storage was considered for this purpose in the determination of the reservoir size. This was done for cost estimation purposes only.

$$TV = NI + OE \tag{A.1}$$

in which TV is the total energy value, NI is the net income of the power entity, and OE is the operation expenses. These operation expenses include direct expenses, depreciation, administration expenses, general expenses, and operation and maintenance costs. The net income is given by

$$NI = \frac{re}{100} \times FC \tag{A.2}$$

in which re is the rentability rate of the power entity in percent, and FC is the fixed capital. This fixed capital includes the investment in both construction and operation of the different components of the system.

The National Development Plan specifies that the energy price must be lowered from its actual value (about Q 0.03 per kw-h) while striving for a rentability rate of the power entity of the order of 12 percent, higher than the present rate. Under these conditions, the total energy value would become

$$TV = 0.12\ FC + OE \tag{A.3}$$

According to the National Development Plan, the total investment planned up to 1979 is Q 137,934,400 including all previous investments but excluding the NLW project. According to plans, the total available energy for 1980, not including the NLW project, will be 1,557.75 million kw-h. Total operation expenses were not given, but they were estimated based on historical data of operation expenses and installed

energy and from estimates made for some of the projects planned for the decade of the seventies. A figure of Q 14,000,000 was obtained for pre-project operation expenses.

To convert the total energy value to a price per kw-h, TV , as given by Equation (A.3) was divided by 85 percent of the 1,557.75 $X10^6$ kw-h estimated for 1979 (15 percent losses are assumed for transmission and distribution). This price per kw-h, including the NLW project, is given in Table A.7 for different rentability rates of the power entity.

TABLE A.7

Energy Prices for 1980 Without the Project, for Different Rentability Rates re

Rentability Rate re in percent	Energy Price in Q/Kw-h
6	0.0169
7	0.0179
8	0.0190
9	0.0200
10	0.0210
11	0.0221
12	0.0231

The price adding El Jocote Project would be computed as follows:

$$EP = \frac{\frac{re}{100}(137\ 934\ 400 + \Delta FC) + (14{,}000\ 000 + \Delta OE)}{(1\ 557\ 750\ 000 \times 0.85 + 0.85\ \Delta E)} \qquad (A.4)$$

in which EP is the energy price in Q/kw-h , ΔFC is the investment to be made in this project, ΔOE are the operation expenses of this project, and ΔE if the annual energy to be produced by this project.

As it can be seen, the energy price is a function of the installed capacity and the reservoir size. Another problem arises here, since the reservoir is to be used also for irrigation purposes and the investment to be made on it should be allocated to both irrigation and power. Various procedures can be followed to find the portion of the cost that should be allocated to each use (22) and, although this subject has given rise to much controversy since none of these methods can be regarded as entirely satisfactory, it is considered that the method of justifiable alternative costs is the most useful (22).

A United Nations report (22) defines this method as follows:

> This procedure consists in apportioning the common investment in terms of what it would cost to obtain the benefits of each of the objectives in the multiple project, by means of separate projects.
>
> The most economic alternative cost of each of the objectives, which in all cases must be "justifiable", must therefore be ascertained. The justifiable limit of the alternative investment is understood to be that which does not exceed the capitalized value of the benefits which it would provide. ...Thus, for the purpose of apportionment, the alternative investment will be taken to be that assessed for an alternative project, or the capitalized value of the estimated benefits. The lower of the two will be taken...

The "justifiable differences" are then obtained for each purpose by subtracting from each justifiable investment that part directly attributable to that use in the multipurpose project, and the apportionment is made based on these differences.

For irrigation, alternative projects would be, for example, the use of water from local streams or the use of groundwater. Since no

data was available for these, only the capitalized value of the estimated benefits was considered as justifiable investment. The justifiable difference was negative, thus indicating the reservoir costs should all be attributed to hydropcwer and that the project would be better off without the irrigation. However, since eliminating the irrigation would not allow for the investigation of the effects of the different forms of irrigation demands (i.e., stochastic, deterministic, dependent, and independent from flows), it was assumed that for political reasons, the government wants to carry along the irrigation part*.

The price of energy including El Jocote Project may now be obtained from Equation (A.4). Prices for rentability rates of the power entity other than 12 percent were also obtained and are shown in Table A.8. The corresponding annual benefits are also included.

Fom Tables A.7 and A.8 it is seen that if the rentability of the power entity is raised to the order of 12 percent, the price of the energy is lowered from its present value both with and without the project, but still remains relatively high**. The National Electrification Plan (1968) strived for an energy price of Q 0.0150 with a net rentability of 10.8 percent, but from the above computations this does not seem feasible with or without the project unless the operation expenses of the power entity are somehow lowered. Since this aspect

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* In the real case, it would pay to make a detailed analysis of the alternatives of providing water from local streams or groundwater. The alternative of conveying water from Chixoy does not seem economical.

** An analysis made with thermal power as the cheapest alternative for El Jocote Project showed that prices would be between those shown in Tables A.7 and A.8.

is outside the scope of this work, it will not be examined in more detail.

TABLE A.8

Energy Prices for 1980 With the Project, for Different Rentability Rates, and Annual Benefits to be Expected from the Project

Rentability Rate re in Percent	Energy Price in Q/kw-h	Annual Benefits in million Q
6	0.0144	11.9
7	0.0156	12.9
8	0.0167	13.8
9	0.0180	14.9
10	0.0191	15.8
11	0.0203	16.8
12	0.0214	17.7

A report from the Economic Commission for Latin America of the United Nations showed that for the year 1964, the average net rentability for the power entities in Central America was of the order of 9 percent. Accepting this rentability as a minimum value, it is seen from Table A.8 that the energy price could be lowered to Q 0.0180/kw-h.

Net Benefits: Based on the foregoing considerations, results shown in Table A.9 were obtained using different rates to discount to present time the stream of costs and benefits during an estimated economic life of 50 years.

TABLE A.9

Benefit-Cost Analysis for El Jocote Project, Assuming an Energy Price of Q 0.018/kw-h and a Net Rentability for the Power Entity of 9 Percent

Discount Rate in Percent r	Actualization Factor $\frac{(1+r)^T - 1}{r(1+r)^T}$	Costs in Million Q			Benefits (Present Value) in Million Q	Net Benefits (Present Value) in Million Q
		Capital	O & M (Present Value)	Total		
6	15.76	124.00	16.40	140.40	246.00	105.60
7	13.80	124.00	14.40	138.40	216.00	77.60
8	12.23	124.00	12.80	136.80	192.00	55.20
9	11.00	124.00	11.45	135.45	172.00	36.55
10	9.90	124.00	10.30	134.30	155.00	20.70
11	9.02	124.00	9.40	133.40	141.00	7.60
12	8.30	124.00	8.65	132.65	132.00	-0.65

Although the national development plan strives for a net power rentability re of the order of 12 percent, the government usually specifies that projects should be evaluated at discount rates r of 9 and 12 percent. The following comparisons give an idea about the trade-offs between power rentability, energy price, and total project return rate.

From Table A.9 it is seen that for a power net rentability of 9 percent and an energy price of Q 0.018/kw-h, the project becomes infeasible for a discount rate of 12 percent. Separate computations showed that for the project to give a return rate of 12 percent, the price of energy should be at least Q 0.0191/kw-h (corresponding to a power rentability of 10 percent). On the other extreme, a low energy price of Q 0.0144/kw-h (corresponding to a 6 percent power rentability) gives a total return rate of 9 percent.

To give both a project return rate and power rentability rate of 12 percent, the energy price would need to be Q 0.021/kw-h. The question that arises is how to evaluate the benefits lost by the country by keeping a relatively high energy price, in terms of foregone industrial development. As it has been stated before, this point is controversial and it will also depend on the price elasticity of demand (the percentage change in the quantity consumed resulting from a price change of one percent) for energy.

For the purpose of this example, it will be assumed that 9 percent is the minimum acceptable value for both total project return rate and power rentability and, therefore, the maximum energy price is assumed to be Q 0.018/kw-h.

A.5 Modified Economic Model

In order to take into account the characteristics of a developing economy as stated in Chapter II, the estimation of net benefits was made using Equation (4.1) for the deterministic linear programming model and Equation (6.5) for the stochastic simulation model. To use these equations, the coefficients of the equations presented in the section about the alternative economic model in Chapter II had to be evaluated first. This was done as follows:

1. Social rate of discount. Using data from the National Development Plan for Equation (2.1), a social rate of discount of 4.3 percent was obtained.
2. Social opportunity cost of capital. Although it was considered that data to evaluate Equation (2.2) was included in several of the reports reviewed for this Appendix, it was not in a form that would have made this task easy. It was estimated that a considerable amount of time (more than the time available for this work) would have been required to put this data in a usable form for Equation (2.2). Instead, the following values were assumed:
   a. $\Sigma d_i = 0.326$
   b. Social value of present consumption of 0.12 (equal to the recommended discount rate)
   c. A constant average rate of return on capital invested in all sectors equal to 0.15

   With the social rate of discount of 4.3 percent, the value of the social opportunity cost of capital is $\theta_g = 1.22$.

3. Social value of net additional income received by sectors. This value is given by Equation (2.7).

The sectors considered for the Guatemalan economy were: agriculture, mining, industry, construction, power and other facilities, trade, transportation, services, and "other." It was assumed that the total benefit for the project will be distributed among three of these sectors: power, industry, and agriculture. Since power is government controlled, P_p is 1.0 and $1-P_p$ is zero. So, only agriculture and industry need to be included in Equation (2.7).

For agriculture, the following values were adopted for the coefficients of Equation (2.7):

a. An average propensity to save equal to 1 minus the income elasticity of demand.

b. An income elasticity of demand for consumption goods of 0.5 (taken from the National Development Plan) indicating that the goods consumed by the sector are necessities.

c. A value of b_{agty} equal to the benefits from irrigation as computed in section A.4.2.

d. An assumed average rate of return on capital of 15 percent.

e. A social rate of discount of 4.3 percent.

f. P_{ag} equal to 25 percent.

P_{ag} is the percent of the extra benefits obtained by the sector which is paid to the government for products and services. In this case, it represents the water charges for the irrigation water. Rather than assuming a specific charge,

25 percent was selected taking into consideration that the more the amount left to the farmers, the greater the incentive for them to move into the project area.

For industry, the values adopted for the coefficients of Equation (2.7) were as follows:

a. An average propensity to save of 13 percent and an average rate of return of 20 percent.

b. An income elasticity of demand of 1.72.

c. A social rate of discount of 4.3 percent

d. P_I equal to zero.

e. A value of b_{ity} assumed to be the difference of the price of energy from "without" to "with project" conditions for a 9 percent power rentability rate (see Tables A.7 and A.8), multiplied by the percentage of the energy consumed by the industrial sector (estimated as 50 percent).

4. Annual revenue from the operation of the project. The coefficients of Equation (2.8) were as follows:

a. For power, the net government revenue is the net benefit as obtained in section A.4.2.

b. For agriculture, b_{agty} and O_{ty} are the benefits and the operation and maintenance costs as obtained in section A.4.2.

c. P_{ag} is 0.25.

5. Shadow wage rates for underemployed agricultural labor. The following considerations were made to estimate the coefficients of Equation (2.10):

a. A type A labor was assumed, i.e., that the workers were to be removed from their own village so that transfer and settling costs, costs for food collection and distribution, and higher wages than the average farm income were assumed. The reason for this was that, once the water resources project is finished, these workers could be the core of the settling considered in the NC Project.

b. Relocation costs were assumed to be covered by the NC Project.

c. The value of $J_1 = W^*_{ag}/W_{co}$ was computed using for W_{co} the salary scale for unskilled construction labor of the National Electrification Institute, and computing W^*_{ag} by dividing the part of the gross national product corresponding to the agricultural sector by the rural population. J_1 was thus estimated to be 0.28.

d. Assuming 20 percent underemployment in the sector, the relationship L_{ag}/L'_{ag} is 0.80.

e. J_2, the added cost due to scarce living facilities near the project as a ratio to W_{co}, was estimated to be 1.2 using the salary scale for difficult conditions of the National Electrification Institute.

f. μ_{ag}, ρ_{ag}, and r are as previously estimated.

6. Shadow rate of foreign exchange. The value of SF in Equation (2.13) was estimated to be 1.05 using the black market rate.

7. Present value of the net effect on the balance of payments. The coefficients of Equation (2.14) to estimate ΔBP_y were

obtained as follows:

a. C_y is the total construction cost of the project as estimated in section A.4.2. The portion of this cost which requires foreign exchange was estimated according to the following percentages: For the reservoir 44 percent, for the power plant 60 percent, for transmission facilities 88 percent, for the tunnel diversion works and conveyance canal 40 percent, and for the irrigation system 25 percent.

b. O_{ty} represent the operation and maintenance costs of the project, as estimated in section A.4.2. The percentage of O_{ty} which requires foreign exchange was assumed as 20 percent in all cases.

c. The percentage of the benefits which goes to import substitution in each sector was estimated assuming that all crops go for local consumption (so the percentage is zero for agricultrue) and that the benefits to industry all go to reduction of imports (ergo this percentage is 100 for industry). It was also assumed that because a hydroelectric plant is used instead of a thermal plant, 70 percent of the net power benefits go to reduction of imports (6).

d. As for the percentage of industrial operation costs which require foreign exchange, they were not taken into consideration because the assumption was made that no extra operational costs are incurred by industry to obtain the benefits from the reduction in energy prices. As for

power, the operation costs are already included in the net annual revenue from the operation of the project, assuming a percentage of 20 percent.

e. Finally, the percentages of the total cost assigned to unskilled labor (ℓy in Equation (2.13)) were assumed as follows: For the reservoir 20 percent, for the power plant 5 percent, zero for transmission works, 20 percent for tunnel construction, diversion works, and conveyance canal, and 45 percent for the irrigation system.

A.6. Metric Equivalents

The equivalents of the metric units used in this work are as follows:

1 millimeter	0.03937 inches
1 meter	3.281 feet
1 kilometer	0.621 miles
1 square meter	10.764 square feet
1 hectare (10,000 square meters)	2.471 acres
1 square kilometer	0.386 square miles
1 cubic meter	35.32 cubic feet
1 million cubic meters	811 acre-feet

A.7. List of Information Sources for the Data Used in This Appendix and in Chapter III

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