MODELLING AND FORECASTING OF WATER DEMANDS

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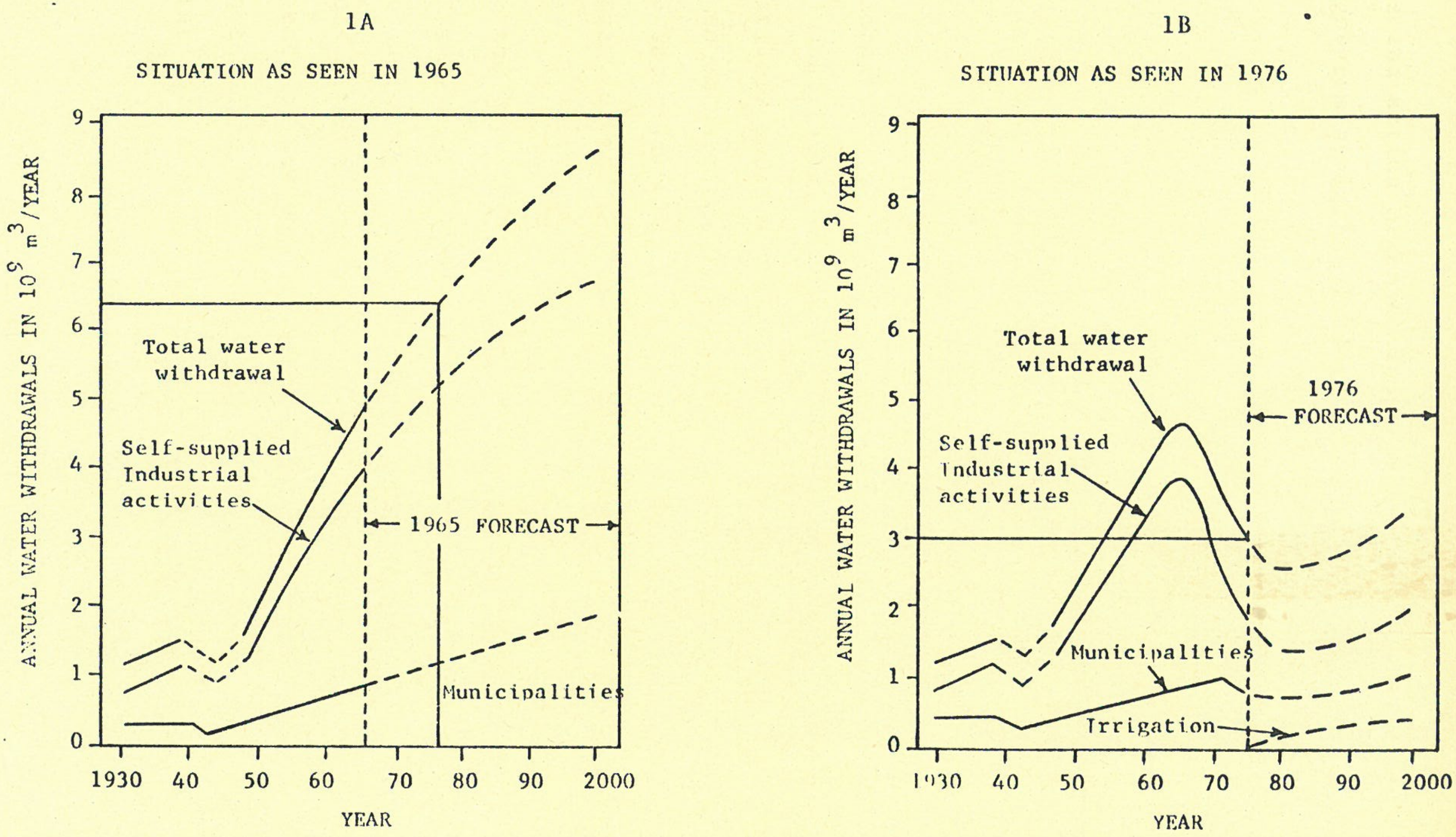
Introduction

If historical trends of population and income per capita continue, there are likely to be significant alterations in the nature of human desires, social values, policies, institutions, and technology. Accompanying these changes will be further increases in the demands for water and water-related goods and services, as well as concommitant conflicts among those competing for the use of water resources.

Estimating water demand relationships is one of the most crucial elements in water resources management. At present, the methodologies used for estimating these relationships are relatively crude. Data collection programmes are generally inadequate. As a consequence, even in some of the more advanced countries, there is only a vague picture of how much and why water is actually used for various purposes. Forecasting methodologies are basically crude, often not consisting of much more than straight line projections of existing trends.

Recent experience in Sweden provides a good illustration of this point (Falkenmark, 1977). The 1965 forecast for the country's future water withdrawals, generally based on trend extrapolation, is shown in figure 1A. Strict environmental

Figure 1 Evolution of water withdrawal in Sweden; actual and according to forecasts in 1965 and 1976 (Falkenmark, 1977)



quality goals and action-oriented programs were established by the Swedish government in the 1960's, and previous legislation regulating the conditions for wastewater disposal was considerably sharpened by the Environmental Protection Act of 1969. A drastic decrease in industrial water withdrawals, and hence in total withdrawals, occurred as a result, as shown in Figure 1B. This result seems to be due to the fact that a reduction of waste discharges was accomplished by water recycling and technological changes in processes rather than by external means of wastewater treatment. It should be noted that this reduction of water withdrawals has taken place in spite of a substantial increase in industrial production over the same period. Thus, within a relatively short period of 10 years, the forecast of water withdrawal proved to be substantially inaccurate, the 1965 forecast of total 1976 water withdrawals in Sweden being about $6.3 \times 10^9 m^3$/year, compared with the actual in 1976 of about $3 \times 10^9 m^3$/year, a little less than half.

What are the ways in which water resources planners can improve their estimates of water demands? More generally, what can be done to accommodate the constantly changing relationships among water use, technology, and institutions on the one hand, and the emergence of new ideas and concepts in water resources management on the other?

One of the most critical challenges is to shift from the more or less traditional supply-oriented *extensive* approach to water resources management to a demand-oriented *intensive* approach (Sewell and Roueche, 1974). The former is characterized by a focus on water supply, for example, a progressive increase in the distance over which water supplies are obtained; as local sources become exhausted, additional water is obtained from farther afield. In this approach, new and expanded water uses are met primarily by developing new sources of supply. Storage reservoirs and long-distance transfers of water are important methods of extending supplies. However, societies are increasingly finding that the most accessible and least expensive supplies have already been developed and that increasingly greater economic, environmental, and social costs are incurred in developing each additional increment of water supply. Supply expansion should not be viewed, therefore, as the only possible response to prospective disequilibria between water demand and water supply.

In contrast to the supply-oriented extensive approach is the demand-oriented intensive approach. The primary objective of the latter is to make the most efficient use of existing water supplies. This means achieving the social goals of society at the lowest social cost, which in turn requires explicit consideration of alternatives on the demand side as well as on the supply side.

The increasing costs of developing water resources and environmental protection indicate the need to conserve, recycle, and reuse water resources, i.e., stimulate the adoption of the demand-oriented approach to water resources management. It has become apparent that water must be treated as a partially substitutable input in industrial, agricultural, municipal (residential, commercial, institutional, etc.), and other water use activities. The possibilities of substituting other inputs for water in the production of goods and services is an area which requires the urgent attention of water resources planners.

The increased interest in the efficient use of water resources has occurred because it is widely realized that water can no longer be considered an inexhaustable gift of nature; that water is indeed a scarce resource similar to other scarce resources. Water users must learn to think of water as a factor input with value similar to electricity, natural gas, food, and other raw materials. They must be induced to reexamine their concepts of the costs involved with the use of water in their activities, both as an input to their activities and as a recipient for disposal of their "leftovers." This holds true whether or not direct payments are made for water withdrawals, for consumptive use of water, and for wastewater discharges.

Basic Definitions for Analysis of Water Demand Relationships

The term "demand" is, unfortunately, used interchangeably with "requirement." The fallacy of considering physical water requirements as unrelated to economic demand stems largely from two misconceptions. The first is that the water user generates water requirements independently of the costs of water to him. The second it that there is only one fixed combination of factor inputs to produce a given good or service, one of which is a fixed quantity of water; no substitution possibilities are presumed to exist. As a consequence of these two misconceptions, most planning efforts in water resources management have concentrated on how best to meet water requirements defined in this manner.

In reality, water and the services provided by water, e.g., for disposal of wastes, are commodities--factor inputs to production and use activities--analogous to other factor inputs, e.g., chemicals, energy, hops, iron ore. Thus, they have values and the demands for them should be considered in the economic sense of demand.

Water demand has four dimensions: (a) water withdrawn at the intake(s) of a given activity; (b) the quantity of that withdrawal that is consumed; (c) the volume and quality discharged; and (d) time as it influences each of the former dimensions. The quantities of water intake, consumptive use, and disposal services are the quantities for which the activity would give up some amount of resources rather than do without them.

To avoid confusion in terminology in this paper, the term "water demand relationships" is introduced. This is to indicate that the amounts of water intake, consumptive use, and wastewater disposal services demanded by an activity are a function of several variables. These variables include: climate; the charge on water withdrawal (intake); the quality of water at the intake; the cost of handling water within the activity; the technology involved in a given productive or service activity; the nature of the product or service (specification or characteristics); level of production; social tastes and behavior; the nature of substitute raw materials; the prices of other factors of production (e.g., energy); value of output (price or prices at which the product(s) and/or services can be or are sold); and standards and/or charges on disposal of wastewater. The use of the term "water demand relationships" illustrates that in all categories and types of water use, and in all socioeconomic systems, there are different combinations of inputs that can be used to produce the desired outputs--products and services--the combinations of which will result in different levels of water withdrawals, consumptive use of water, and disposal of wastes to water bodies, both per unit of product or service and in total. Moreover, the quantity demanded relates also to the value of water in its alternative uses, and is time dependent, even for a given activity or type of water user with fixed technology.

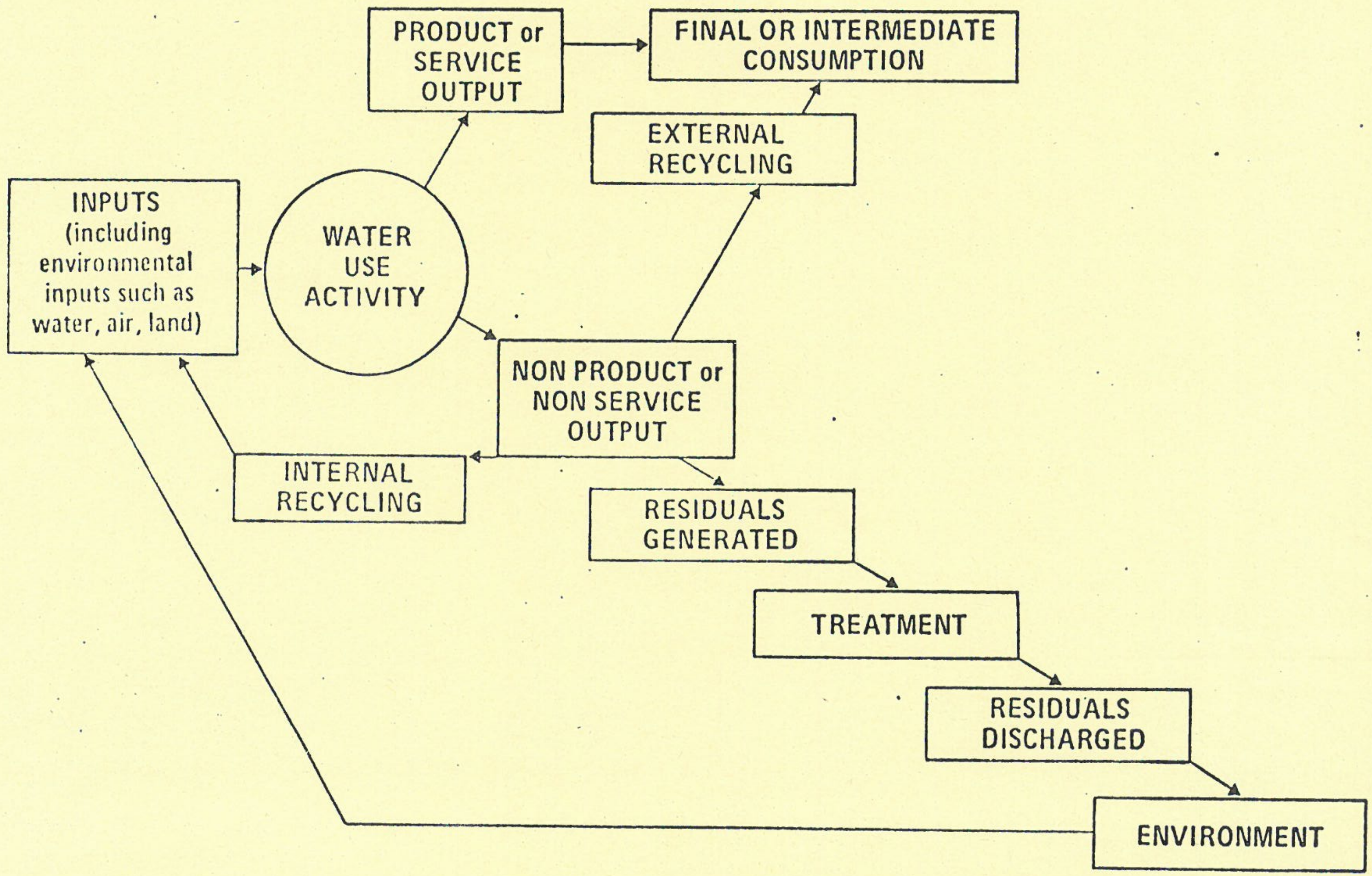
An important point should be raised in relation to the water quantity/water quality relationships "at both ends," e.g., on the input and output sides of a water use activity.

All water use activities which are discussed in this paper result in the generation of residuals, as shown in figure 2, because no production or service activity transforms all of its inputs into the desired products or services. The remaining flows of material and energy from the activity are termed nonproduct outputs. If the economic value of a nonproduct output is nil or is less than the cost of collecting, processing, and transporting it for input into the same or another activity, the nonproduct output is termed a residual. Hence, whether a nonproduct output is a residual or not depends on the relative costs of alternative materials and energy which can be used instead of the nonproduct output. These costs in turn depend on the current level of technology in the society and on various governmental policies, both of which can change over time.

It should be emphasized that there are technological, physical, and economic interrelationships among the two basic types of residuals--materials and energy--and among the three states of the former--liquid, gaseous, and solid (Bower, 1977). For example, a residual generated in one state can be transformed into one or more residuals in another state.

To an economist a <u>demand</u> for a factor input such as water involves the relationship between the quantity of a factor taken and price, by definition. Whether the charges actually imposed for water withdrawal, consumptive use, and disposal of residuals to water bodies make a significant difference in the

Figure 2. Input-output Relationships for a Water Use Activity



quantities demanded at a particular point in time, and whether these charges over the long run can affect the rate of growth of water demand and hence the need for investments for expanding water supply and wastewater treatment, depends on many factors. These factors include: how large the charges are; the role of charges in a given socioeconomic system; the substitution possibilities available in various production and service activities; technologial innovation; and the extent to which the characteristics of final demand can be modified.

"Water demand modelling" is defined as the systematic examination of water demand relationships. These relationships can assume a wide range of possible forms, and can be classified in numerous ways. The objective of modelling is to build the simplest model possible which will adequately address the question in a given context.

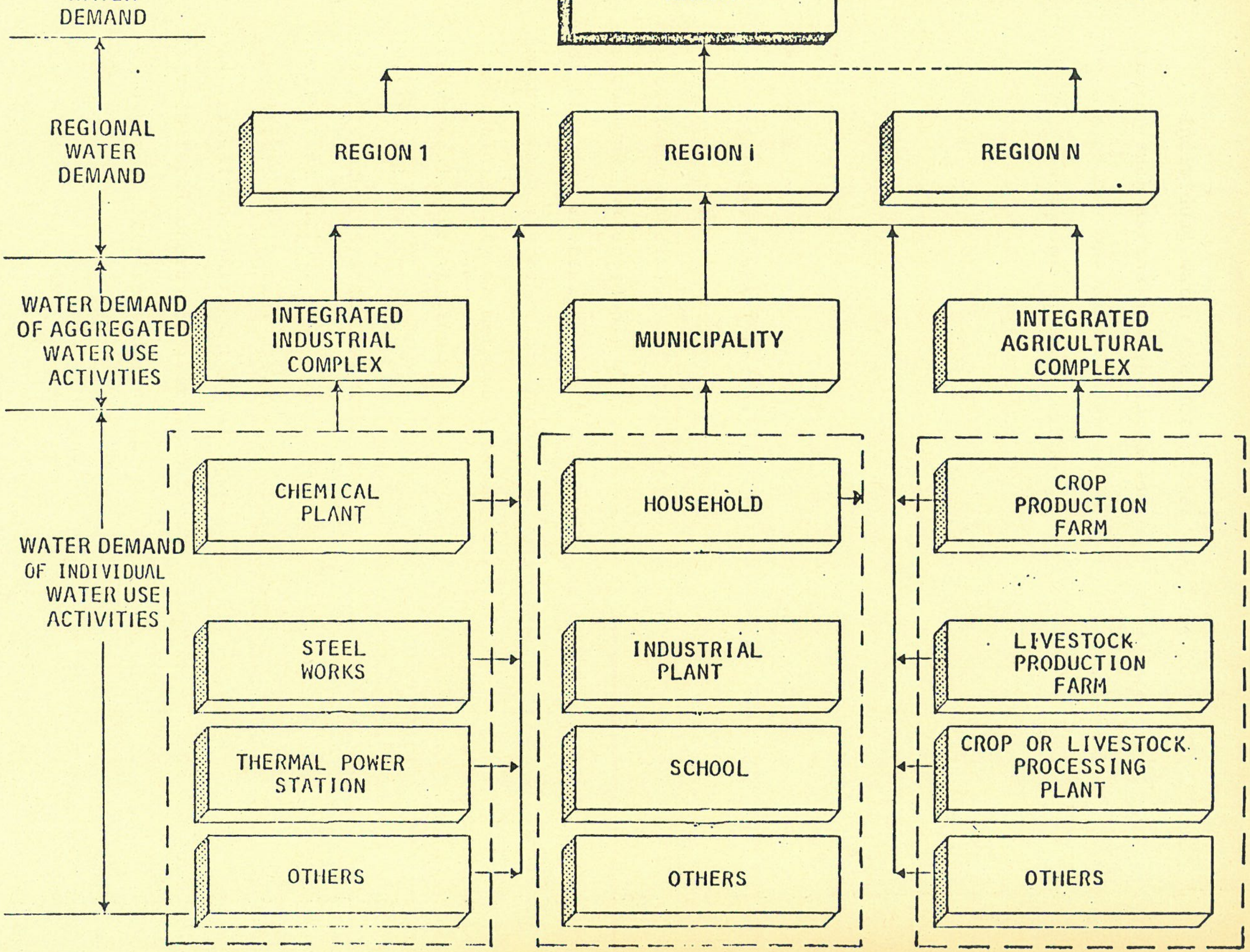
Most often this question involves forecasting water demands at one or more future points in time in relation to levels of population and production associated with a five-year plan in a centrally planned economy and with projections of economic activities in other economies. The development of a water demand relationship for an activity provides the basis for forecasting. Thus, forecasting water demand by an activity requires forecasting the values of the variables in the model of water demand relationships for that activity. Any consistent set of forecast values for these variables can be substituted into the model, which then results in a forecast of water demand.

Until now, forecasts of water use--withdrawal, consumptive use, wastewater disposal--have most often been based on application of water use coefficients, i.e., units of water and wastewater per capita, per employee, per ton of product output, per ton of raw material processed, per monetary value of product. These coefficients were <u>not</u> based on the development of explicit water demand relationships and were often assumed to be constant over time, or were varied in an arbitrary manner.

As discussed later in this paper, modelling and forecasting of water demands focus on <u>unit water demands</u> (per unit of raw material input, per unit of product output, per capita, etc.), which are analogous to <u>water use coefficients</u>. However, the important distinction is that unit water demands are based on water demand relationships in which one or more variables relating to water charges, wastewater disposal charges, and water handling costs are <u>explicitly</u> included. In contrast, the coefficients are not based on functional relationships and charge and cost variables are included only implicitly, if at all.

For purpose of exposition, there are four levels at which water demand relationships may be analyzed. These are: (1) individual water use activity; (2) aggregated water use activity; (3) region; and (4) nation. Figure 3 illustrates how the demands of individual water activities build up sequentially into the demands of aggregated activities, regional water demands, and finally national demands for water and water-related services.

Figure 5. The Different Levels of Water Demand Analysis



Individual water use activities are individual decision units, such as the household, a factory, or a farm. Each unit produces one or more goods and/or services, and a fundamental assumption is that the unit's objective is to do so in the most efficient way, however efficiency may be defined in a given socioeconomic context. To the extent that water is an input into this process, the challenge is to determine the best ways in which water can be combined with other factor inputs to produce the desired outputs of goods or services by the activity.

Aggregated water use activities are comprised of individual activities served by a common system, such as all of the activities receiving water through the distribution system of a communal water supply agency, or all of the activities discharging wastewaters into a communal sewerage system. The most common aggregate of individual water use activities is the municipality or metropolitan area, in which residential, commercial, institutional, industrial, recreational water use activities are served by water from and/or discharge wastewater to a communal system. Other types of aggregated water use activities include industrial complexes in which multiple industrial activities discharge wastewaters to a common system, an irrigation district consisting of a number of separate agricultural operations, an agricultural complex consisting of a number of different operations but under a single management.

The distinguishing characteristic of an aggregated water use activity is that all of the individual activities within the aggregated unit are served from a common intake system and/or by a common effluent discharge system. Thus, one can analyze the water demand of a municipality, an agricultural complex, or industrial complex.

The problems of analyzing water demand discussed in this paper focus on water demands of individual and aggregated water use activities. The reason is that these are the only levels at which water demand can be explicitly modelled and analyzed as a function of various demand determining variables, with explicit consideration given to substitution possibilities. It is exceedingly important to recognize that these are the fundamental levels of demand analysis, as has been emphasized by Sewell and Bower (1968), Whitford (1968), Grima (1972), and many others. Given an understanding of water demands at these levels, one can proceed to address questions raised at the regional and national levels.

The quantity of water demanded at the regional level consists of the composite demands of the various individual and aggregate water use activities within the region, allowing for sequential reuse of water within the region. There may not be aggregated agricultural or industrial complexes within a region. In such regions the quantity of water demanded is merely the reflection of the demands by various individual industrial plants, agricultural activities, individual residences, institutions, recreational activities, and municipalities in the region, where the municipalities may represent the only aggregated water use activities.

Water demand at the national level is comprised of the demands of all regions located within the boundaries of a nation. National totals as such, for example for particular types of water use activities, have little significance for decisions. But they can reflect alternative conditions and governmental policies.

Basic Approaches to Modelling Water Demand

Water demand analysis can be facilitated by modelling, which is the attempt to depict the basic factors underlying the demand for water, and to show how these factors influence each other as well as water demand itself. Given an alteration in a demand determining factor, such models can produce a forecast of the likely water demand associated with that change. Models used in water demand analysis vary in their complexity, ranging from relatively simple linear relationships to highly complex ones based on the detailed analysis of the unit production processes and the associated water utilization system of an individual water use activity. The challenge is to select a model which is no more complex than is required to answer the question at issue.

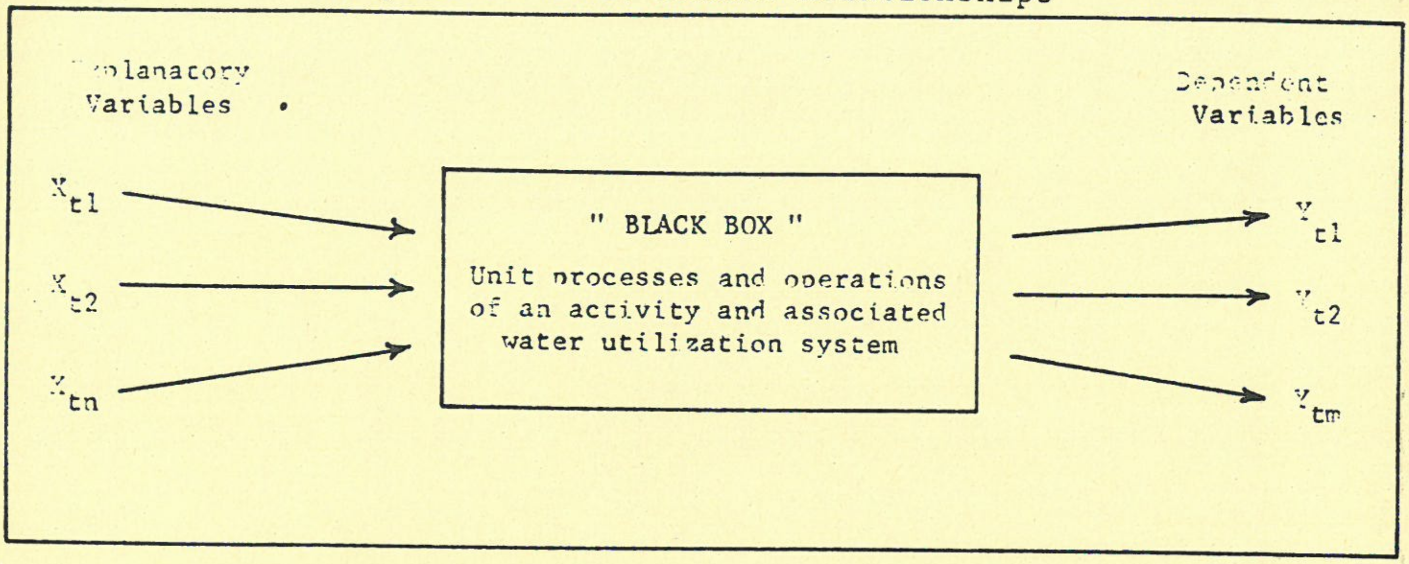
Water demand models should be looked upon as a vital part of the water management planner's kit of tools. It should be made clear that these models by themselves do not provide an answer to the question of what are the rational (economically efficient, socially justified) levels of future demands for water. Water demand models are "estimating relationships" and care must be exercised in their use in the overall context of water resources planning and management. The water resources planner must have a good understanding of the data base and the approach used in deriving a given water demand model. Above all, he must exercise care in extrapolating beyond the range of experience (the sample) underlying the model.

There are two basic approaches to modelling water demand relationships: (1) the statistical; and (2) the engineering-economic unit process approach. The latter has two major subcategories: (a) engineering design; and (b) various types of mathematical programming. The following discussion briefly describes these approaches and some of the methodological problems associated with them.

Statistical Approach

The statistical approach can be applied to individual water use activities and to some aggregated water use activities. The activity whose water demand is being modelled is conceptualized as a "black box," as shown in figure 4. The variables shown as inputs to the box represent the explanatory variables; those shown as the outputs reflect the dependent variables.

Figure 4. Representation of the "Black Box" Concept in Statistical Analysis of Water Demand Relationships



The essence of a black box is that one can see the outside, but not the inside. The analyst uses data describing what goes into a production or service activity and what comes out; what changes and what stays the same. The details of the unit processes and unit operations of the production or service activity and the associated water utilization system remain essentially unknown.

As discussed previously, water demand has four dimensions: (1) the amount of water withdrawn at the intake of a given activity; (2) the amount of water withdrawn that is consumed; (3) the amount of wastewater discharged by the activity and its characteristics; and (4) time as it influences each of the former dimensions. Therefore, in a statistical approach to modelling water demand relationships, there are at least three dependent variables, all of which should, in principle, be considered simultaneously. As many explanatory variables as possible should be explicitly included in the development of a statistical water demand relationship.

The time-honored tool which is most often used when using the statistical approach to modelling water demand relationships is regression analysis. Regression analysis is concerned with one-way relationships between dependent and independent variables, where the expected value of one dependent variable is related to nonrandom values of the explanatory variables.

The following comments are related to the practical application of regression analysis. First, no amount of sophisticated statistical analysis can compensate for gross inadequacies in the data. Because the data problem is fundamental, water demand analysts usually devote a considerable amount of time and resources to collecting data and to making adjustments in the raw data in order to ensure consistency and comparability. The systematic collection of the types of data needed for statistical models is a problem in all countries, and is the primary factor limiting application of the statistical approach to modelling water demand relationships.

In regression analysis, the data base is either time series or cross-section data. A time series is a set of data ordered in time, typically with observations made at regular intervals, for example, each census year, annually, monthly, or daily, related to a single activity or a few similar activities. Cross-section data refer to observations made at one point in time, or averaged over a certain period of time (e.g., year), relating to a sample of water-using activities of a given type. In the first case, the temporal variation is used for making statistical inferences about the effects of certain variables. Time series and cross-section data are not mutually exclusive for one may have a time sequence of cross-section samples. Pooling time series and cross-section data is an area of considerable theoretical and empirical interest in the analysis of water demand relationships.

Second, there are several critical assumptions underlying regression models which are very often violated by the available data, especially the time series data. The difficulties that beset the use of time series have primarily the four following causes.

The first is the simultaneity of economic relations. Observed values of economic variables are usually generated by a system of economic relations. It is well known that it may be impossible to estimate some of these relations. Classical least square estimation of a single structural relation, which ignores the others, yields, in general, inconsistent and biased estimates.

The second cause of difficulty is errors occurring in the observed values of the variables. Reported values of some variables are often subject to error resulting from different collection techniques or are only approximations to unobservable variables specified in the theoretical relationship to be estimated. Some methods have been advanced to deal with errors in variables in particular situations, but there remains much to be done in this area.

The third cause of difficulty is multicollinearity. Many time series are often closely correlated with one another (are multicollinear), owing to the common factors that influence all economic activities. If the explanatory variables are multicollinear, it would be impossible to determine with any confidence the influence of each of them using the usual least squares regression procedure.

The fourth cause of difficulty is the basic assumption that errors from regression are serially independent, that is, uncorrelated over time. In time series data, autocorrelated errors are likely to occur if the explanatory variables are autocorrelated.

Cross-section data are often superior to time series data for estimating water demand relationships for several reasons. Cross-section data contain large variations in some variables whose variations over time are only moderate and often subject to trend. The size of a cross-section sample of data can usually be increased enough to make sampling variance relatively negligible. Multicollinearity among variables in a set of cross-section data is often less acute than among corresponding variables in a time series. Finally, the problem of autocorrelation does not arise, simply because the order of observation has no meaning.

All these comments concerning the use of regression analysis in the development of statistical water demand relationships are mentioned simply to point out that statistical methods should not be applied mechanically, and should not be applied without first making a careful review of the available data base. It should also be stressed that the statistically derived demand relationships can be applied for forecasting purposes only where it can be assumed that the structural pattern of past water demand relationships will continue in the future. This condition is an underlying assumption of all statistically derived water demand relationships, independent of the degree of sophistication of the methods used for their development.

Engineering-economic Unit Process Approach

The discussion of water demand relationships to this point viewed the activity as a black box, with a set of inputs, including water, and a set of outputs consisting of goods and/or services and residuals. In reality, virtually all activities are comprised of a set of unit processes and operations. For example, iron and steel production involves such unit processes as coking, sintering, iron-making, steel-making, rolling, and finishing. Household water use involves such unit processes as drinking, food preparation, bathing, toilet flushing, dish-washing, and clothes washing. The crop-producing agricultural operation consists of a certain number of individual fields exhibiting different soil and topographic conditions, and different crops. Superimposed on these are such unit processes as planting, cultivating, irrigating, harvesting. Each of these unit processes or operations, within an industrial, a residential, or an agricultural activity, is characterized by its water intake, water consumption, and residuals discharge, which represent a materials and energy balance for water in relation to a unit of output from, or unit of input to, a given process or operation. In agriculture, for example, water consumption is the evapotranspiration rate which relates the amount of water effectively used by a crop to the crop yield, for a given soil and set of management practices.

Most of these unit processes and operations use water and generate liquid residuals. In addition, there are specific water quality characteristics desired and a specific time pattern of use related to each unit process and operation. Thus, the water demand for the entire activity, e.g., the aggregate black box, is the aggregate of the water demands of the individual processes and operations. Depending on quality demanded, recirculation and cross-flows are possible. Relationships between extent of recirculation and cost, extent of recirculation and quality, and extent of recirculation and consumptive use must be developed for each unit process and operation, in order to have the base for the analysis of possible substitutions among elements of the activity's water utilization system.

In order to reflect accurately the effects of various technological, economic, policy, and other changes on the water demand of a given water use activity, it is necessary to calculate a material and energy balance for each alternative and to derive the corresponding water-related quantities. Sometimes these quantities are simply indicated among the technological characteristics of a given process.

It should be stressed that there are no generally applicable rules to tell how far the water demand analyst should go in dividing an individual water use activity into unit processes and operations. The general principle is to go into the study of individual unit processes until the value of additional information is equal to the cost of obtaining it. As usual, it depends on the objectives and format of a particular water demand analysis.

The engineering-economic unit process approach to modelling water demand relationships is based on the engineering and economic analysis of both the individual unit process and the associated water utilization system: what purposes water serves at each unit process or operation of the production or service activity, where it goes, how the individual unit processes of the activity and/or components of the water utilization system can be changed, and how much such changes will cost. The activity is no longer a "black box."

There are two analytical methods of implementing the engineering-economic unit process approach: (1) engineering design; and (2) various types of mathematical programming. Until a certain point in the implementation, both methods follow the same path. Thus, the preliminary investigations of the activity, the development of material and energy balances for unit processes and operations, and the specification of factor inputs and their costs and residuals of interest always comprise necessary steps for developing water demand relationships by the economic-engineering approach.

The engineering design method of estimating water demand relationships entails varying the inputs which determine the quantity and quality of water used, and for each combination of inputs identifying the least cost way of producing the given level of output. For each combination of inputs, the analyst can determine water demand and thus a point on the demand function for water intake, consumptive use, and wastewater disposal services.

This task involves identifying the technological options open for changing water use by the given activity and estimating the costs of making such changes. It is necessary to determine whether the savings in costs of intake water and wastewater discharge justify the increased costs associated with making the change. If the charge for water withdrawn increases, the question arises as to whether it is cheaper to continue using the same amount of water or to spend funds to reduce water intake. Similarly, if discharge standards become more stringent and/or an effluent charge exists, the problem is to determine the least cost way of meeting the standards and then to determine how much additional reduction is justified in order to reduce the effluent charges to be paid. The engineer must determine how flows and waste loads can be reduced, what the different levels of such reduction will cost, and how such changes impact the quantities and types of other factor inputs in the production process. The decision rule is to change water use patterns and other factor inputs whenever it lowers the total cost of producing the output.

Because production of goods or services is usually a function of many variables, an exhaustive search for the least cost solution at any given level of output can be long and complex. If the analyst wants to examine "m" different values for each of the "n" inputs, there are m^n combinations to be analyzed, Each combination requires a solution to an engineering design problem.

When there are several inputs and numerous possible values for each, rules are required to limit the number of combinations to be studied. In the past this has generally been done on the basis of professional engineering judgment, and the usefulness of many engineering studies of water use is limited by the failure to consider a wide enough variety of options.

<u>Mathematical</u> <u>programming</u> methods have significant potential for use in the study of water demand relationships. There are several case studies available at IIASA and other institutions and in the literature which illustrate the practical application of mathematical programming methods for estimating water demand relationships.

In addition to the usual limitations of mathematical programming methods, especially linear programming, a few words of caution are necessary concerning their use for estimation of water demand relationships. (See Whittington, 1978.) Many of these difficulties are not unique to mathematical programming; the same problems arise in the use of statistical and engineering design methods of modelling water demand relationships. They are mentioned here because the formulation and detail of programming models make some of the assumptions underlying the modelling effort particularly apparent.

The first difficulty concerns the treatment of capital. One of the principal resource inputs to any production process is obviously the capital cost per unit of output based upon the annual output of the plant. The annualization factor is often, however, simply a rule of thumb. The real cost of capital to a water use activity and the appropriate depreciation rate for the capital are often very difficult to determine. Both can vary significantly among activities and among countries due to such factors as imperfect markets, different expectations about inflation, and different tax arrangements. Unfortunately, the results of linear programming models of water use activities may be sensitive to variations in capital costs well within the margin of error of the annualization factor.

The second difficulty concerns that of applying the model to existing water use activities. The majority of model applications to date are for new "grassroots" activities. In this case the model selects the optimal combination of types of unit processes and operations and the associated water use system with the assumption that a new plant is to be designed and all possibilities are open. When the modelling approach is used for an existing activity, the options are more limited. The costs of continuing to operate existing activities may be very different than for new activities. Linear programming models of water use activities could conceivably reflect such considerations, but data on the economic value of existing capital can be very difficult to obtain and are subject to serious measurement problems. The major problem in analyzing water demand relationships for existing activities is the site-specific nature of some of the relevant variables.

Concluding Remarks

Water resources management faces problems of increasing number and complexity. The scope of problems has expanded enormously, particularly as a result of the rapid increase in population and industrial production, the spread of urbanization, the emergence of new kinds of water uses, and the increase in disposable personal income. Irrigation is a key issue of water resources development around the world. Moreover, in many places in developed and developing countries, water quality has deteriorated seriously, which has implications for water uses. Although relatively large volumes of water may be available, without modification of quality they are often suitable only for a limited range of uses.

As countries undertake more and larger projects to meet their increasing water uses, the physical and economic limitations of natural water supplies become apparent. When water is readily available, and thus relatively inexpensive, the inefficient use of water may not be critical. But with the increasing costs of supplying water, its efficient use becomes an important issue in relation to a society's always limited resources and the demands of sectors other than water on those resources. Information on water demand is essential if water is to be allocated to its most productive uses.

As pointed out in this paper, the demand side of water resources management deserves much more attention than it has been given in the past. It should be made clear, however, that knowledge of the subject is only partial and limited. The field is open for additional investigation and research.

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