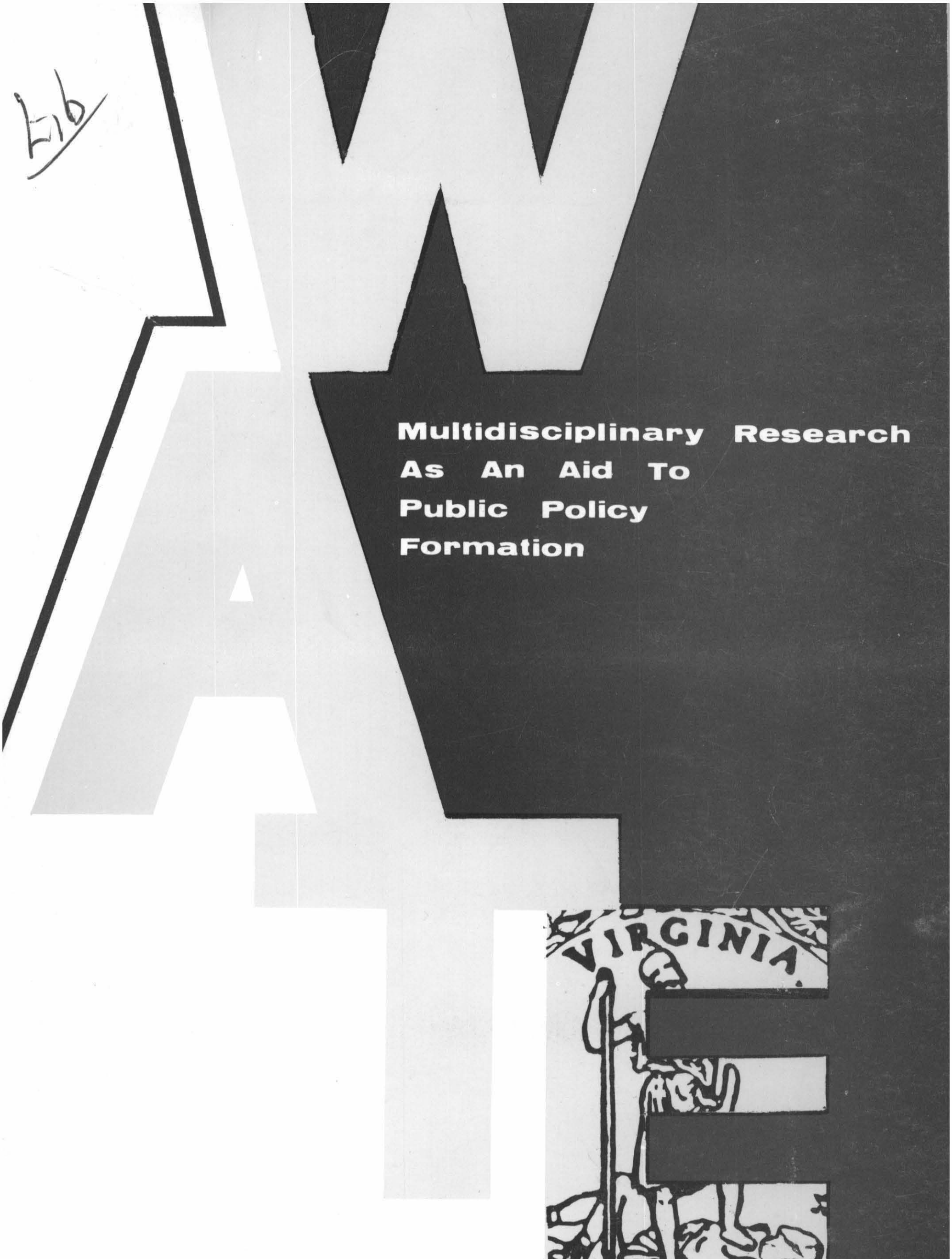

Multidisciplinary Research As An Aid To Public Policy Formation

Cover designed by David J. E. Greene and John Wisnosky

Multidisciplinary Research As An Aid To Public Policy Formation

Seminar on Multidisciplinary Research as an Aid to Public Policy Formation, Virginia Polytechnic Institute, Blacksburg, 1965.

MULTIDISCIPLINARY RESEARCH
AS AN AID TO
PUBLIC POLICY FORMATION

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PREFACE

This report contains the papers presented at the Seminar on Multidisciplinary Research as an Aid to Public Policy Formation. The Seminar was sponsored by the Water Resources Research Center at Virginia Polytechnic Institute. Financial support was with funds provided by the United States Department of the Interior as authorized under the Water Resources Act of 1964, Public Law 88-379.

The purpose of the Seminar was to stimulate multidisciplinary research in water resources by illustrating the spectra of research opportunities and needs in the field, particularly to those members of the University community who have not heretofore been active in water resources research. In addition it suggested potentially promising research topics to both staff and students and aided in creating an atmosphere conducive to fruitful cooperative research in water resources.

The planning of the Seminar was done by Professor F. E. McJunkin and Dr. James M. Wiggert, Department of Civil Engineering; and William R. Walker, Director, Water Resources Research Center.

TABLE OF CONTENTS

Page

7148 101

OPTIMUM WATER USE - A MULTIDISCIPLINARY APPROACH

by

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The character of water problem is changing. The traditional water use patterns are being upset by growing urbanization, advancing technology, rising incomes, and increasing leisure. The present and future metropolitan areas and the associated nonagricultural development are, and will remain, very unevenly distributed in space. The cities and industries seldom grow in a systematic fashion; the municipal and industrial water demands change discontinuously over time. Water use is a complex phenomenon; factors affecting it or affected by it are many. It depends on physical conditions, technological circumstances, population changes, social and economic attitudes, and value judgments expressed through the political process.

The Southeastern United States is passing through a marked transition from an economy which has been primarily agrarian to one which is substantially urban-industrial. However, the change has proceeded unevenly in different parts of the region. The level and composition of water use vary considerably from one part of the region to another. Since 1940, there has been a rapid decline in the rural farm population and a substantial migration to urban areas. This shift of population is significant in terms of the location and magnitude of land and water use. The growing demographic, social, and economic complexes are generating ever-increasing water demands for urban and industrial uses, recreation, and conservation. There has been a transfer of appreciable quantities of land and water to nonagricultural uses. The adjustment is still in progress. The re-allocation of water resources to new uses will have an important bearing on resolving or creating future conflicts between agricultural and other uses of water. It is hoped that the direction of change will be toward optimum resource use. For example, at the end of the period of adjustment agricultural production will presumably be concentrated in areas where soils and climates are most favorable. The transition provides an opportunity to guide the movement towards the best use of resources. Measures to facilitate the inevitable change and making the transition to the desired alternative uses as smooth as possible deserve serious interdisciplinary study. The problems of adjustment are being raised in continuously changing circumstances and have to be conceived in a dynamic, rather than static, framework.

OPTIMUM USE

Is there an optimal pattern of water use for a region? Conventional approaches are incapable of specifying the social optimum resource use in terms that are practical and operational (1). The difficulty arises mainly from the state of social and behavioral sciences. These are not sufficiently advanced to offer a satisfactory conceptual and analytical framework for human behavior. We have not yet arrived at a stage where the social and political behavior of men can be made susceptible to optimizing techniques; it would require better theories of human behavior than are available at present. Social optimum in resource use can at best be stated only partially and incompletely. There are conceptual as well as measurement difficulties in finding the optimal course of action.

The determination of optimum water use in an operational sense is exceedingly difficult. From the very beginning, one is faced with the crucial issues of the selection of objectives and criteria, specification of economic and social values, and the problems of risk and uncertainty. One must find means for the quantitative projections of hydrology, economy, technology, and institutions and forecast changes in population size and preferences. Each of these areas provides a promising field for cooperative research between engineers, economists, and other social scientists. The optimizing decision is determined by the interaction of social objectives determined through the relative preferences of a society and the physical, functional characteristics of the system used to accomplish these objectives.

Social Objectives

The determination of the best use of water resources depends on the social objective and cannot be derived independently of it. The first step is, therefore, to define the objective. This is not always easy. Development can proceed along a variety of paths. Different objectives signify different routes to development. Depending on the objective, one may arrive at very different solutions. Objectives guide the search for alternatives, provide criteria for the evaluation of different courses of action and govern the selection of the optimum system. To choose the wrong objective is to solve the wrong problem.

The choice of objectives must be made in accordance with the totality of environment prevailing in a society. The entire complex of political, social and economic considerations need be taken into account. In this respect, political and social considerations are usually more significant than purely economic and technological ones. It is difficult to ascertain what the people are for. The present practice of relying on pressure groups, advisory committees, and interpretation of elections for the expression of people's preferences leaves much to be desired. Direct sampling of communities may be more desirable. There is, however, the formidable problem of translating individual values into social choices.

The objectives are derived from a value system. It will be too optimistic to expect general agreement on any one set of values. In most cases, there is not one but several goals that are pursued jointly by public water policy. There are common as well as conflicting interests among the users of water. The conflict usually arises from the weights that are assigned to opposing values, especially to economic efficiency and noneconomic objectives. Should water resources be used for the creation of economic activity, for mass recreation, or for the protection of wilderness for its own sake? Unfortunately there is no body of theory that can guide us in choosing a good set of objectives. Even if one is given a set of objectives, there is no sure way of determining whether the set is good. In an affluent society, there is growing emphasis on extra economic values within the group of objectives. With increasing emphasis on the quality of environment, growing interest in the quality of life, and rising sophistication of outlook, purely economic considerations play a progressively smaller role. In such circumstances, glorifications of economic efficiency for its own sake cannot persist. It may be that equality of consumption will tend to become a dominant goal in an affluent society that professes the democratic creed (1).

In the case of conflict, the objective function can only be arrived at by assigning specific weights to opposing values. The prescription of weights should be made as a policy decision and should reflect balancing of political, economic, and technological realities. However, for a better understanding of the conflicts and for bringing them into sharp focus, consideration of a single optimal solution is not enough. A range of possible solutions satisfying alternative formulations of the objective function, obtained by assigning different weights to different objectives, need be considered. This type of analysis, if in quantitative terms, would assess the cost of satisfying a particular objective in terms of sacrificing other values. The decision models should be formulated in technical (that is, physical, chemical, biological) units without the use of price concept. If presented to the people or the decision makers in the form of a schedule (that is, a range of products available at a range of costs), they will be in a better position to express their preferences than if they were to decide, in the abstract, between fish and industry.

Functional Relationships

Establishing an optimal use plan is beset with difficulties because of the deficiencies in the present state of knowledge concerning the physical, functional relationships among the variables of the system which describe its behavior. These structural relationships are the production functions of economics. Some of these functions depend on the techniques of production and some on human behavior. The physical relationships vary greatly with location due to spatial factors, and with time due to the dynamic nature of the problem. These relationships are almost always empirical and are actually the result of interaction of many structural relationships. Cooperative research between engineers and economists is needed to estimate the structural parameters involved. The relationships are always of a statistical nature and require statistical methods for the estimation of the parameters. A few examples of the deficiencies are given in the following paragraphs.

In humid areas, the profitability of supplemental irrigation in an absolute sense is as yet undetermined. Reliable data on changes in productivity and costs associated with supplemental irrigation are not available. Without a knowledge of yield response, cost-price relationships, and requisite farm organization and management, it is difficult to forecast the future extent of irrigation.

Water quality management involves forecasting of changes in the chemical, physical, biological, and hydraulic properties of water systems. There are deficiencies in the basic understanding of the phenomena involved. A general theory for the prediction of dynamic changes in the stream characteristics caused by the augmentation or reduction of flow, addition of waste loads, creation of impoundments, and other changes in the system has not yet been developed.

Methods of developing a functional relationship between the type of recreation, water quality, distance from the recreation area, and availability of other recreational facilities in the vicinity have not yet been discovered. Meaningful measures for relating the quality of water supply, disease, and health are lacking. The examples can be multiplied.

Other Factors of Production

Optimum water use cannot be determined in isolation. Within the framework of regional development, water is only one of several components. Water is seldom the only limiting factor; its optimum use is always conditioned by the interactions with other factors of production. Wollman has shown that it is not the relative productivity of water in its various uses but the supply of complementary factors of production and their productivities in alternative uses which govern the direction of optimum water use. When viewed in this larger setting, optimum water use plan for a region will probably contain certain uses in which value added per unit of water is relatively low (2). This will particularly be true of the Southeast where water is generally not in short supply.

OPTIMAL POLICIES

The optimum development of water resources will not come of its own accord; it will not be achieved by the unseen hand of economic forces; it can only be brought about by the long arm of deliberate public policy. This will require conscious, systematic, and comprehensive planning. What is needed is, therefore, an optimizing approach to public policy making. Water policy problems can be split into two parts: those relating to public investment in water projects and those regulating the decision-making process of self-supplied water firms.

Public investment in water projects constitutes only a part, not even a predominant one, of the total investment in water resources. Water is largely self-supplied, 47 percent of all irrigation, 87 percent of water used in manufacturing, and almost all of that used in steam electric generation. Investment criteria for the optimal allocation of public resources have figured prominently during recent years. The proposed criteria have been based on the propositions of welfare economics with economic efficiency as the social objective. In actual practice, the public policies governing the development of nation's water resources are not determined solely on the basis of economic efficiency. In reality, there is no general agreement on the objectives of public investment among the various agencies concerned with the planning and development of water resources.

To understand its implications for water policy, it is necessary to recognize that water resource development is only partially in the exchange system. In the private sector, the decisions about the production and use of water are largely internal within the self-supplying firms and are not expressed through an articulated water market. Similarly public investment in water resource development is seldom motivated solely by market considerations. Furthermore, the value of some of the goods and services flowing from water resource projects is not adequately measured by market prices. Market valuations are either inadequate or irrelevant for measuring aesthetic, conservational, and psychological elements of development. Finally, institutional considerations permeate all phases of water policy. They are closely associated with the economic and technological aspects and are difficult to isolate and quantify. The concern of water policy should, therefore, be less with market mechanism and more with institutional arrangements, and legal and administrative structures, for example, regulations and standards, water rights, registration and permits, required to regulate the decision-making process of self-supplied water firms, both public and private.

Dynamic Aspects

Water resource development and management problems are essentially dynamic. Growth itself is fundamentally a process of change. With time the population, economy, and technology change; so do preferences, institutions, and objectives. The changes are sometimes even dramatic. These changes are reflected in a continually shifting pattern of water demand. Forces are set into motion to bring about a shift in the direction of water use from a lower, less desirable purpose to a more productive, higher one. A difficult problem in water resources management is to ensure security of investments, prevent waste, and at the same time maintain flexibility, avoid commitment to immutable and long-term uses. The problem of maintaining flexibility versus security provides a fruitful area of research for lawyers, engineers, and economists.

Approaches to the formulation of public water policy should also be viewed in a dynamic framework. Different policies imply different strategies for water resource development and have different consequences for the future states of the system, which in turn determine the courses of action which are optimal at later times. No single set of policies is the best under all circumstances. The validity of a specific policy is largely dependent on the stage of development that a region has attained. Policies motivated only by the immediate problems ignore the cumulative process of development. A valid comparison of alternative policies requires tracing the effects of the corresponding sequences of decisions through time.

Quality: The New Dimension

In the Southeast there is no prospect of an overall water shortage; the quantities of water withdrawn are not likely to be a factor limiting regional development. The concern will rather be over water quality. Eventually water quality will enjoin a state of interdependence on various uses and users of water resources. It will become the link between various interests dependent on common bodies of water and prove to be the unifying force for the coordinated development of water resources. The existing conceptual, analytical, and institutional framework for dealing with water resource problems has been evolved for a water-shortage economy with undue preoccupation with quantitative considerations. How far these forms are capable of dealing effectively with the new dimensions of water quality remains to be seen. The traditional concepts and institutions seem to be largely inapplicable to the radically changed environment of an urban-industrial society which is well-endowed with water resources. Basic concepts and techniques of analysis with water quality as the more important dimension of water resources need be formulated. Entirely new concepts of economics and law must be developed, along with new institutions with adequate jurisdiction and powers.

One important area of public water policy is the setting of quality criteria. Water is a complex commodity completely lacking in uniformity and no single set of rules is applicable to all waters. Setting of standards is essentially an act of compromise and calls for the careful balancing of a wide variety of conflicting interests. Standards for environmental control are essentially judgments of social value and should not be regarded as absolutes. To set uniform standards for a country as geographically diversified as the United States without also setting up unreasonable road blocks to practical use of water in some parts of the nation is impossible. It will conceivably advance some segments of the economy while working hardships on others. For example, one of the approaches to the formulation of optimal policy for water quality management is the specialization of streams, or sections of streams, for specific uses. This is usually implemented through a system of stream classification. A uniformly prescribed standard may be more stringent than justified for some streams and less than adequate for others. The consequence of overcontrol is greater social cost in the benefits foregone; the result of undercontrol is the foreclosing of more productive opportunities. Research is needed to establish just what constitutes adequate control in any given situation. Should we have a uniform yardstick (for example, 7 day 10 year minimum streamflow) for all streams irrespective of their low flow characteristics? Or should the duration and return period of low flows be made variables of the problem and their values obtained as a part of the solution depending on the probability and magnitude of the actual and potential damages? Why should the dissolved oxygen criterion be set arbitrarily at any specific value? One should be interested less in a specific minimum dissolved oxygen requirement and more in the pattern of development postulated in the assumed rate, the amount of investment it represented, and the likelihood of its being realized in a reasonable period of time. The social cost of varying the minimum requirement should play a decisive role in setting a standard.

Specialization of streams, or sections of streams, for specific uses has some merit and deserves further consideration. We have become so enamoured of the multiple-purpose concept that we refuse to admit that single-purpose developments may still have some virtue. To provide for every purpose on every project does not make much sense. Sections of a stream best-suited to domestic water supply or recreation could be set aside for these purposes, rather than attempting to furnish second-rate recreation and third-rate domestic water supply everywhere. A tolerably well-balanced development should be the aim on a regional, rather than on a local project by project, basis. A logical extension of this idea is the concept of sequential use which permits the adaptation of water use to its quality. That is, priorities of different uses along different sections of a stream are arranged in some practical sequence on the basis of decreasing quality requirements.

ANALYTICAL TECHNIQUES

Water resource problems exhibit great complexity, diversity, and variety. Water resource systems contain meteorological, technological, economic, and social components. They are under the influence of a great many variables which interact in many and varied ways. The traditional engineering and economic approaches are proving to be too limiting for the solution of present day problems of ever-increasing complexity. It is becoming necessary to proceed along new and unorthodox lines. Only very recently have the theory of probability, time series analysis, regression and correlation techniques, theory of sampling, and computer simulation been used on a large scale in the analysis of water resource systems. Techniques of analysis will have to be further developed to assess the relative value of water in its various uses, from both an economic and social point of view.

Value in Use and Loss Functions

A fundamental problem is to ascertain and measure the values associated with each potential use. A related problem is the determination of the value of different increments of water for different purposes. There will always be a large portion of social benefits and costs for which monetary evaluation will be meaningless. Many of the rapidly growing demands at present fall into this category. They have received little attention with respect to the evaluation of benefits and costs. Major examples are water quality management, public water supplies, and recreation. Alternative costs are often used as a measure of benefits for some of the outputs of water resource projects, but rules for their correct application have never been rigorously defined. Research is also needed to determine the sensitivity of different uses to departures from target levels. Loss functions associated with short-term deficits in domestic and industrial water supplies, irrigation, and short-term changes in reservoir elevations from the level established for optimum recreational use need be developed. These will enable the incorporation of shortages into design.

Models

Quantitative models are a useful tool of analysis. Depending on the purpose to be served, the models used in water resources development can be classified into three categories. The first stage involves getting an insight into the working of the economy of a region in order to be able to project demands for water resource products and services. Implicit in it are the assumptions about the rate of growth of the region and the role assigned to it in the economy of the nation as a whole. Only in this larger setting can proper objectives be fixed, the future predicted, and the optimum use of water determined. Federal agencies have commissioned the preparation of the projections of population and economic activity of several water resource regions. The economic base studies have made available large amounts of information on the economic characteristics of a region; their applicability and pertinence to determining water requirements are surprisingly restricted. Translating economic projections into water demands is beset with great difficulties.

A regional input-output model with unit water requirements for major economic sectors has been developed for California (3). Input-output models have serious shortcomings. Water as a commodity is subject to a changing technology that affects both the conditions of demand and supply. Process changes permitting a reduction in the quantity or quality of water used, changes in production functions eliminating water use altogether, and changes in industrial water use technology to increase reuse and recycling will have major impact on net water requirements. It is, therefore, not possible to say that a product requires a specific quantity of water. Furthermore, the projections of water requirements do not consider the functional relationship between prices and physical quantities of water and its change over time.

Second stage models are descriptive models: analytic and simulation. They give a quantitative description of what happens in the real world. The promise of analytical models is so far unfulfilled. Based on simplifying assumptions, models are constructed which are supposed to reproduce certain aspects of physical and economic reality. To achieve a workable model, the phenomena and processes must of necessity be stripped to their barest essentials. Such models have been extensively developed. Up to the present, most models (Thomann's model is a notable exception) have little of fundamental importance to exhibit in the way of application to actual data. Nearly all of them rely on simplified, skeletonized and constructed data. Adequate field data to confirm or refute such models are lacking. There is great need for empirical work to assist in distinguishing between various theoretical models, and possibly to suggest new ones. The extension and strengthening of the theoretical foundations should, however, continue. Much of our meager knowledge about the dynamic behavior requires a firmer theoretical basis as well as added empirical information.

One research technique that has yielded consistently useful results is computer simulation. Simulation is the most powerful method at present available for the solution of complex, real problems. Increasingly larger electronic computers have opened up the possibility of analysing models having large number of variables and relationships. It is now possible to study simultaneously the complex interplay of several variables on the performance of a system. The concepts of welfare economics can now be made operational on a wide scale. As the fundamental character of simulation is dynamic, the model used can represent reality in its essential details. Studies in depth of many aspects of water resources have become possible for the first time by utilizing electronic computers, both analog and digital. A whole new era of scientific water resource management is opening up with the recent advances in computer technology. Research need be directed in three directions: developing practical forms of programming techniques to handle extremely general solutions, reducing actual computing costs, and devising techniques of sampling from very high-dimensional spaces.

Third stage models are prescriptive models. The power of prescription which a model can provide depends to a large extent on the possibility of tracing the consequences of many alternative assumptions pertaining to some aspects of institutions, economy, or technology. An attempt is made to determine the necessary changes that need be effected to remove the bottlenecks that prevent the system from attaining its maximum potential. To indicate the optimum direction for public policy, a quantitative model is necessary but not sufficient. The implementation lies in the sphere of the political process. Institutional factors affect water use, and hasten or delay shifts required by social and economic considerations. It is likely that institutional arrangements will determine the distribution of water, and hence the pattern of its use, without any regard for the best use of water resources in the context of regional economy. Many of the existing institutions and public policies should be altered in response to the changed circumstances.

Uncertainty

Uncertainty is an essential element in all water system planning. Appropriate treatment of uncertainty is a critical factor in achieving efficient allocation of resources. There are three kinds of uncertainty in water resource development: cost estimation, hydrologic, and benefit estimation. Hydrologic uncertainty does not increase with time and the probabilities involved can be measured or inferred quantitatively. There have been significant advances in developing techniques to allow for this type of uncertainty. The application of stocastic processes to hydrologic phenomena is a promising field of research for hydrologists and statisticians. Uncertainties created by technological, economic, preference, policy, and institutional changes increase with time. The probabilities of such changes are not amenable to quantitative measurement. There are no satisfactory decision rules for dealing with this type of uncertainty. Great errors in arriving at an optimum use of water can, however, result from failure to predict these changes accurately, especially the changes in technology and economic circumstances.

WATER AND REGIONAL DEVELOPMENT

Water resource development is being proposed as a means of arresting the relative decline of some settled regions, for example, Appalachia, and for stimulating and promoting growth in others. Water in some minimal quantities is an essential precondition for any development. But beyond these indispensable limits, the promotional impact of abundant supplies of good-quality water on the location of industrial activity is not established. American industry has been, and is, on the move. However there appears to be no correlation between these movements and the availability of water. Industries vary within very wide limits in their requirements of water. In some industries, opportunities for conserving water, for effective treatment of wastes, and for reuse are so extensive that the availability of water has a very low impact on the decisions about location.

There is urgent need to develop suitable methodologies and criteria to assess the impact of investment in water resources on the local and regional economy. This will require that appropriate objectives of regional development be established and their relationship with the overall national objectives be determined. This will certainly involve a significant departure from the objective of economic efficiency. Regional development is not considered to be a strictly economic objective in the context of economic efficiency. It cannot be incorporated easily into the framework of analysis. Here we are confronted with another difficulty. The changes in regional economy as a result of investment in water resources shall have to be, by definition, large. The goods and services added by water projects will have substantial effect on prices and income redistribution. Means of measuring economic values that result from large increases in production are lacking. Furthermore, in the context of regional growth, the assumption of full employment of resources is questionable. The methods of measuring social cost of resources under partial employment are inadequate. In short, a conceptual and analytical framework to deal with regional development adequately is yet to be developed.

The problems of optimum use of water resources are those of water, land, technology, and people -- and of their interactions and feedbacks. Significant progress has been made in the analysis of some phases of these problems. A framework in which the many factors involved can be interrelated and integrated still remains to be developed. The remaining problems are inherently challenging and provide opportunities for creative research and experimentation in many fields. The growing importance of the water problem and the increasing magnitude of the economic, social stakes in its solution should provide sufficient motivation for accepting the challenge.

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DISCUSSANT

by

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For one to say that he was not for optimum water use nor for a multidisciplinary approach would be about the same as saying one was against motherhood and for sin. I do not wish to be put in this category. However, I do wish to raise a question on how much closer we are likely to come to reaching an optimum water use through a multidisciplinary approach by following suggestions in this paper. As was noted at the conclusion, "A framework in which the many factors involved can be interrelated and integrated still remains to be developed."

Dr. Sherwani is to be commended for bringing together in one place and, presenting as a sort of a review, previously existing information on water, problems of determining optimum use, social objectives and the like. For the most part, this is rather familiar ground.

I was looking forward to Dr. Sherwani laying out the path for us to follow in the multidisciplinary manner (that is what the title implied) and what I find is more or less a plea that we ought to get together and see if we can't come up with something. True, he does discuss the use of three categories of models with a digression in one place when he says, "Research need be directed in three directions: developing practical forms of programming techniques to handle extremely general solutions, reducing actual computing costs, and devising techniques of sampling from very high-dimensional spaces." Possibly this is related to optimum water use but to the uninitiated at least, it appears to be much more related to research in a specialized area of statistics and computer use with no real indication of usefulness in water research.

Hardly anyone will quarrel with the notion that present day computer technology has ". . . opened up the possibility of analyzing models having large number of variables and relationship." I could even go along with the idea that computer simulation has yielded useful results (though I would not say it has done so consistently). But I do wish to take exception to the statement, "Simulation is the most powerful method at present available for the solution of complex, real problems." Putting it mildly, that is a powerful statement.

I simply do not wish to be carried away with a single method. "The" solution arrived at through simulation must be many solutions and you take your pick. In other words, the solution you get depends on the values placed on the variables. How does one know when to stop changing these values? What really happens is that one gets many alternative solutions with the decision still to be made as to which is the best.

It is pointed out that water use is a complex phenomenon -- depending on physical conditions, technological circumstances, population changes, social and economic attitudes and value judgments expressed through the political process. I submit that when one starts quantifying these variables to determine the optimum water use through simulation, it becomes an almost endless task.

Finally, I would like to conclude by noting that I seriously doubt the best use of water resources can be (nor should be) determined without regard for the existing institutional arrangements as is implied. To do so would suggest a different form of economic system than we currently have.

SURVEY OF THE THEORY OF EXTREMES AS APPLIED TO HYDROLOGY

by

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The statistical theory of extreme values deals with the behaviour of the largest and the smallest observations in a series and serves for the forecast for extremes. As all statistical theories it is based on the assumption that the prevailing conditions will be valid in the future for which we want to provide, say in the construction of dikes, dams, hydroelectric plants, reservoirs, etc., etc. Then trends and <u>real</u> cyclical movements must be eliminated from the data. The knowledge of the mean values is often insufficient for the solutions of such technical problems because the extreme values are decisive.

The theory of extreme values has successfully been applied to windspeeds, rain-falls, wave-heights, atmospheric pressures, temperatures, discharges of a river, size of boulders in a sand pit, oldest ages, stresses on a tanker, corrosion in pipe lines, fatigue and breaking strength of metals.

Instead of these specific applications we will outline here the general theory, which may serve in all these cases. The theory consists of three parts, considerations which are distribution free, the exact and the asymptotic theory.

Exceedances

The theory of exceedances requires no knowledge on the initial distribution and states the probability w (n, m, N, x) that the mth among n observations of a continuous variable ordered in <u>de</u>creasing magnitude is <u>exceeded</u> x times in N future observations. The expected number of exceedances is

$$E(x) = mN/(n+1)$$

The median number $\check{x}$ in the case $N = n$ is $\check{x} = m - 1$. A forecast of the number of exceedances is more precise for the largest than for the median observation. If $N = n$ is large, and $p = m/N$ remains fixed the distribution of x becomes normal with expectation m and variance $2m(1 - p)$. If $N = n$ is large and m remains fixed, the corresponding <u>law of rare exceedances</u> is similar to Poisson's law of rare events. The expectation is m and the variance 2m.

Two general results of the theory of exceedances are: in 50 percent of all cases the largest of n passed observations will not be exceeded in $N = n$ future observations. The probability that the largest of n passed observations will be exceeded in $N = n$ future observations converges to 3/4. These methods are of interest if we are concerned only in the number of cases that exceed a given observation and not in their size.

For an unlimited continuous distribution the largest value will increase with the sample size n. For distributions which possess the first two moments the increase will be less than $\sqrt{n/2}$ times the initial standard deviation.

Statistical Prerequisites

The following general statistical notions are used: The probabilities $F(x)$ (and $P(x)$) that a statistical variable is less (greater or equal) than a fixed value x, the density functions $f(x) = F'(x)$, the <u>intensity function</u>

$$\mu(x) = f(x)/P(x) > f(x) \geqq 0$$

and the <u>return period</u>

$$T(x) = 1/P(x) > 1$$

of a value equal to or greater than x. This is the mean number of observations necessary to obtain once such a value. If the observations are made equidistant in time T(x) is a time. At the medium value $\check{x}$ of the variable we have $T(x) = 2$ and T(x) increases with x.

All practical applications of statistical theories are greatly facilitated by the use of probability paper. Let the function F(x) be of the form $F[\alpha(x - \theta)]$, α and θ being parameters such that

$$y = \alpha(x - \theta)$$

is a reduced variable without dimension. Let

$$F(x) = \Phi(y)$$

then this function can be tabulated. A probability paper in its simplest form consists of the linear scale x on the ordinate, y and $\Phi(y)$ on the abscissa and T(x) on an upper parallel line. The criterion for the acceptance of a statistical theory consists in the verification of the straight line

$$x = \theta + y/\alpha$$

checked by control curves based on the standard deviation of the mth values and of the return periods. If the aim of the investigation is to forecast the mth observation in increasing magnitude should be plotted at the expected cumulative frequency

$$E(\ F(x_m)\ ) = m/(n + 1)$$

Other plotting positions have been proposed. They are justified for other purposes. But then the return period of the largest value exceed systematically the number of observations. This spreads the distribution over a larger period than the number of observations. For example the usual plotting position $(m \div \frac{1}{2})/n$ acts as if instead of n values we had observed 2n values which is absurd and lead to catastrophic economic consequences (Benson).

Exact Theory

We define the characteristic largest value θ_n in n observations by

$$F(\theta_n) = 1 - 1/n$$

and the extremal intensity function α_n by

$$\alpha_n = n \quad f(\theta_n)$$

The exact probability functions $\Phi_n(x)$ and $\Pi_n(x)$ of the largest and the smallest of n independent observations are

$$\Phi_n(x) = F^n(x); \quad \Pi_n(x) = P^n(x)$$

If the initial distribution is symmetrical, then the distribution of the largest value is symmetrical to the distribution of the smallest one. More generally, to any distribution of the largest value, we can construct a corresponding distribution of the smallest value by changing the sign of x and corresponding changes in the parameters; for example, an upper limit becomes a lower one and vice-versa. This <u>symmetry principle</u> reduces the study of the extreme value to that of the largest one.

For consecutive values of n the curves representing $F^n(x)$ are shifted to the right and depend in an increasing amount only on the behaviour of $F(x)$ towards very large values of x. The curves $F^n(x)$ become more (less) concentrated if the extremal intensity α_n increases (decreases) with n. In the first (second) case the precision of a largest value increases (decreases) with the sample size n from which it is taken.

The probability function of the largest values becomes at the characteristic largest value even for moderate sample sizes

$$\Phi_n(\theta_n) = 1/e$$

Therefore, the median largest value $\breve{x}_n$ exceeds the characteristic one.

If Hopital's Rule holds for the initial distribution and for large x in the form

$$\mu(x) \rightarrow -\frac{d\, \ell g\, f(x)}{dx}$$

(distributions of the exponential type) the modal largest value $\breve{x}_n$ converges to the characteristic largest value θ_n.

Numerous tables of the probability and density functions, the expectation, median and variance of the largest values as functions of n exist for the normal distribution (Pearson). Similar tables for the exponential, log normal and gamma distributions can easily be constructed. For the exponential and the logistic distributions the characteristic largest value θ_n is lgn while the extremal intensity is unity. For the normal distribution

$$\theta_n \longrightarrow \sqrt{2 \lg (0,\ 4n)} \text{ and } \alpha_n \rightarrow \theta_n$$

For a known initial distribution, the exact distribution of extreme values for n observations gives a simple criterion for the rejection of outliers.

Asymptotic Theory

The problem is how does $F^n(x)$ behave if n and x increase? We want to find: $\lim_{n \to \infty} \Phi_n(x) = \Phi(x)$

However the exponent in the probability function

$$\Phi_n(x) = e^{n \lg F(x)}$$

becomes then indetermined. Therefore we have to introduce conditions. The usual method is to postulate the <u>stability</u> which requires that the maximum of the largest value should have the same distribution as the largest value itself except for a linear transformation of the variable. We have to find a solution of the functional equation

$$\phi^n(x) = \phi(a_n x + b_n)$$

where Φ is the unknown asymptotic distribution of the largest value and $a_n > 0$ and b_n are unknown functions of the sample size n, assumed to be large.

There are three and only three solutions of this equation, i.e. asymptotic distributions of extreme values. They are shown in the following table, where $\Phi(x)$ stands for the asymptotic probability of the largest values to be less than x and $\Pi(x)$ for the asymptotic probability of the smallest value to be equal to or larger than x.

THE TRINITY THEOREM

	Largest Values	Conditions	Smallest Values	Conditions
Typ	$-\lg \Phi(x) = e^{-y}$		$-\lg \Pi(x) = e^{y}$	
Expon.	$e^{-\alpha(x-\theta)}$	$\alpha > 0$ $-\infty < x < \infty$	$e^{\alpha(x-\theta)}$	$\alpha > 0$ $-\infty < x < \infty$
Cauchy	$\left[\frac{\theta - \varepsilon}{x - \varepsilon}\right]^k$	$\theta > \varepsilon \quad x \geqq \varepsilon$ $\kappa > 0$	$\left[\frac{\omega - \theta}{\omega - x}\right]^k$	$\theta < \omega;\ \chi \leqq \omega$ $\kappa > 0$
Limited	$\left[\frac{\omega - x}{\omega - \theta}\right]^k$	$\omega > \theta;\ x \leqq \omega$ $\kappa > 0$	$\left[\frac{x - \varepsilon}{\theta - \varepsilon}\right]^k$	$\varepsilon < \theta;\ x \geqq \varepsilon$ $\kappa > 0$

The parameters are chosen in such a way that

$$\Phi(\theta) = \Pi(\theta) = i/e$$

The parameters ω (and ε) stand for the upper (lower) limit; finally k has no dimension. The three asymptotic distributions of extremes corresponds to three types of initial distributions, namely those where the probability functions converge to unity in about the same way as e^{-x} converges to zero (exponential type), those which have a longer tail so that not all moments exist (Gauchy type) and those which possess an upper (lower) limit.

Necessary and sufficient conditions have been found for the convergence of the exact to one or the other of the asymptotic distributions. If none of these conditions are fulfilled an asymptotic distribution does not exist.

The exact theory was based on the assumption of independence. Here this condition is modified. The asymptotic theory is still valid if a few neighbouring observations are dependent. The specific aspect of the asymptotic theory consists in the fact that it can be used even if the initial distribution is unknown and the extreme observations are the only data which are at our disposal. The second and the third distributions are related to the first one by logarithmic transformation. On this basis extreme value probability papers have been constructed which facilitate the choice of distribution.

Applications to Hydrology and Oceanography

We define the flood as the largest daily discharge of a river, in a year, and the drought as the smallest daily discharge during a year. For such yearly observations the return period is the number of years. The first two distributions of the largest values have been used for the floods, waveheights and the wind-speeds, the third distribution of the smallest values for droughts.

In the first asymptotic distribution of largest values the most probable largest value is equal to the characteristic one and $1/\alpha$ is the slope of the straight line

$$x = \theta + y/\alpha$$

plotted on extremal paper. Since for large values of x

$$y \sim \lg T$$

<u>the floods increase as a linear function of the return period.</u> This relation allows to express the design flood in terms of return period and inversely. The choice of the double of the largest observed floods as design flood implies the squaring of the period under observation. This extremely costly procedure has to be rejected.

The estimation of the two parameters by maximum likelihood leads to a complicated system of approximations, and weighs the smallest values heavier than the largest ones, while the corrected method of moments requires only the usual computation of the mean and standard deviation. In some cases the second asymptotic distribution gives a better fit but in this case there is a limit $\varepsilon \geqq 0$ and its estimation is very complicated. What is worse this estimation of the slope k in

$$\lg(x - \varepsilon) = \lg(\theta - \varepsilon) + y/k$$

depends upon ε. The estimate of ε must be positive and smaller than the smallest observation x_1. Therefore this value should be used in the estimation procedure (this principle holds for any limited distribution).

In most cases it can be assumed that $\varepsilon = 0$. Thus the logarithmof the floods increase asymptotically as a linear function of the return period, i.e. much quicker than in the previous cases. The estimation of the parameters in the second distribution is further complicated by the fact that the higher moments do not exist. Statistical and geophysical studies will be necessary to solve the decision problem whether

$$\varepsilon = 0,\ k = k_o \text{ or } \varepsilon = \varepsilon_1 > 0,\ k = k_1$$

and the choice between the two alternative distributions.

If the floods vary only in proportion one to two or three no graphical decision of the goodness of fit is possible. For reasons of simplicity the first distribution is preferred.

The first and second distribution has been used for the largest discharge of a river and for the construction of dams, reservoirs and hydroelectric plants and dikes. The opposite problem of droughts has been successfully analysed by the third asymptotic distribution of smallest values.

The first asymptotic theory of the smallest value holds for the minima of temperature and pressure. According to the third asymptotic distribution the probability $\Pi(x)$ of a drought less than x is

$$\Pi(x) = e^{-\left(\frac{x - \varepsilon}{\theta - \varepsilon}\right)^k}$$

the transformation $\Pi(x) = e^{-e^y}$ allows use of logarithmic extremal probability paper. If the lower limit is 0 the logarithm of the drought decreases as a linear function of the logarithm of the return period. The forecast of droughts depends largely on the estimation of the lower limit. The case $\varepsilon = 0$ leads always to a more severe forecast than the case $\varepsilon > 0$. Here too the estimation of k depends on the estimation of ε.

The forecast of the severity of droughts is important for the construction of reservoirs which should be workable even in the absence of rainfall and for irrigation and the prevention of pollution created by industry.

Both theories have been successfully applied to rivers all over Europe, in China, India, Thailand, the U.S.A., and New Zealand. It seems that the rivers know the theory. It remains to convince the engineers - not only in underdeveloped countries - of the validity of the theory.

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DISCUSSANT

by

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The Theory of Extreme Values has been so adequately presented by Dr. Gumbel that I do not intend discussing it at all. Instead I will use this time to discuss some applications of the theory.

It surprised me, seeing that Dr. Gumbel is from New York City, that no mention was made of the fact that the Theory of Extreme Values is applicable to water reservoirs. At lunch he admitted that he had never really analysed the New York City reservoir situation but felt certain that the return time for a "water crisis" was quite small.

At the last Water Resources Research Center Technical Advisory Committee meeting, the problem of planning an urban sewerage system was discussed. It is quite clear that it is the extreme values which are of interest here. One is not concerned with whether or not the system is adequate on the average but rather how often one can expect the system to be inadequate. The distribution of the extreme values for water run-off due to rainfall can be obtained. A similar distribution for consumer and industrial wastes can also be obtained. A trend, predicting the future extremal distributions can also be obtained. This would aid in predicting how often one can expect the system to be inadequate five, ten or more years hence.

Extreme value theory can also be misused. In a recent colloquium some results on the probability distribution of dissolved oxygen in a stream was presented. A criticism made was that one did not really care about the probability distribution but would rather know how often the dissolved oxygen would go below 3 ppm (the minimum requirement for healthy fish). This is quite incorrect. Fish can live for brief periods with less than 3 ppm. We need the entire distribution in order to predict how long the fish will have less than 4 ppm, 3 ppm, 2 ppm, etc.

So that I will not conclude on a negative point, let me say what I feel was the major contribution of Dr. Gumbel's talk. In this room were engineers who often bring data to our statistical consulting laboratory. Some were unaware that questions concerning extreme values could be answered. They were therefore satisfied with the usual statistical analysis; tests of hypothesis or confidence intervals. From these they had been inferring the answers to the questions they really wanted answered. Now these engineers realize that Extreme Value Theory exists and what type of questions it can answer. They will therefore no longer be content with the "usual" statistical analysis.

ESTUARINE WATER POLLUTION CONTROL VIA SYSTEMS ANALYSIS

by

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INTRODUCTION

The topic of this seminar is particularly appropriate in today's investigations of the interactions between decision making bodies and the scientific and engineering sectors. There is a definitive need for the integration of sanitary engineering with a variety of other disciplines including operations research, system analysis, and econometrics. To particularize this need, this paper will utilize the Delaware Estuary Comprehensive Study (DECS) as an illustration. The Study will be briefly reviewed and the methodology for the formulation and solution of the water pollution control problem will be outlined. Finally, some research needs that are particularly appropriate to the study of the Delaware Estuary will be presented and discussed.

THE DELAWARE ESTUARY COMPREHENSIVE STUDY

Under Section (2)a of the Water Pollution Control Act, the Federal Government is charged with the responsibility for developing comprehensive water pollution control plans for the major river basins in the country. As part of such development, the DECS began during the summer of 1962.

The region surrounding the Delaware Estuary (which runs for approximately 86 miles from the head of tidewater at Trenton, N. J. to the entrance to Delaware Bay) contains a large metropolitan and industrial complex. There are several hundred waste discharges along the length of the estuary, although the major portion of the waste load is accounted for by about fifty sources. Water uses include municipal withdrawals in the upper end of the estuary, some limited commercial and sport fishing, boating and industrial water for boiler feed and for cooling. The quality of water generally is excellent at the head of tide but deteriorates rapidly as one approaches the Philadelphia Metropolitan area. Quality remains poor (dissolved oxygen (DO) levels close to zero) through the Philadelphia area and south through the industrial complex. The recovery zone begins in the vicinity of the Pennsylvania-Delaware State line although restoration of quality is not always completed before the entrance to the Delaware Estuary.

Analytical Procedures

It became apparent in the Study that such a complex system could only be adequately understood if it were modeled in a relatively vigorous manner. A mathematical model[1] was constructed to describe the waste input - water quality output relationships for an estuarine situation. The model was then applied specifically to the Delaware Estuary.

Figure 1 indicates the thirty reaches of the Delaware used in the computational procedure. The model is basically an ordered set of linear systems which respond to an external stimulus (waste discharge) and produce an output (in terms of DO, salinity, alkalinity, etc.). The response of the system to the imposition of waste sources is through the physical characteristics of the stream; in this case, fresh water inflow, tidal diffusion, reaeration (for DO) and the cross-sectional areas and sectional volumes.

The techniques include technical procedure for forecasting the estuarine water quality on both a short-term and a long-term basis. Major emphasis in the DECS has been on

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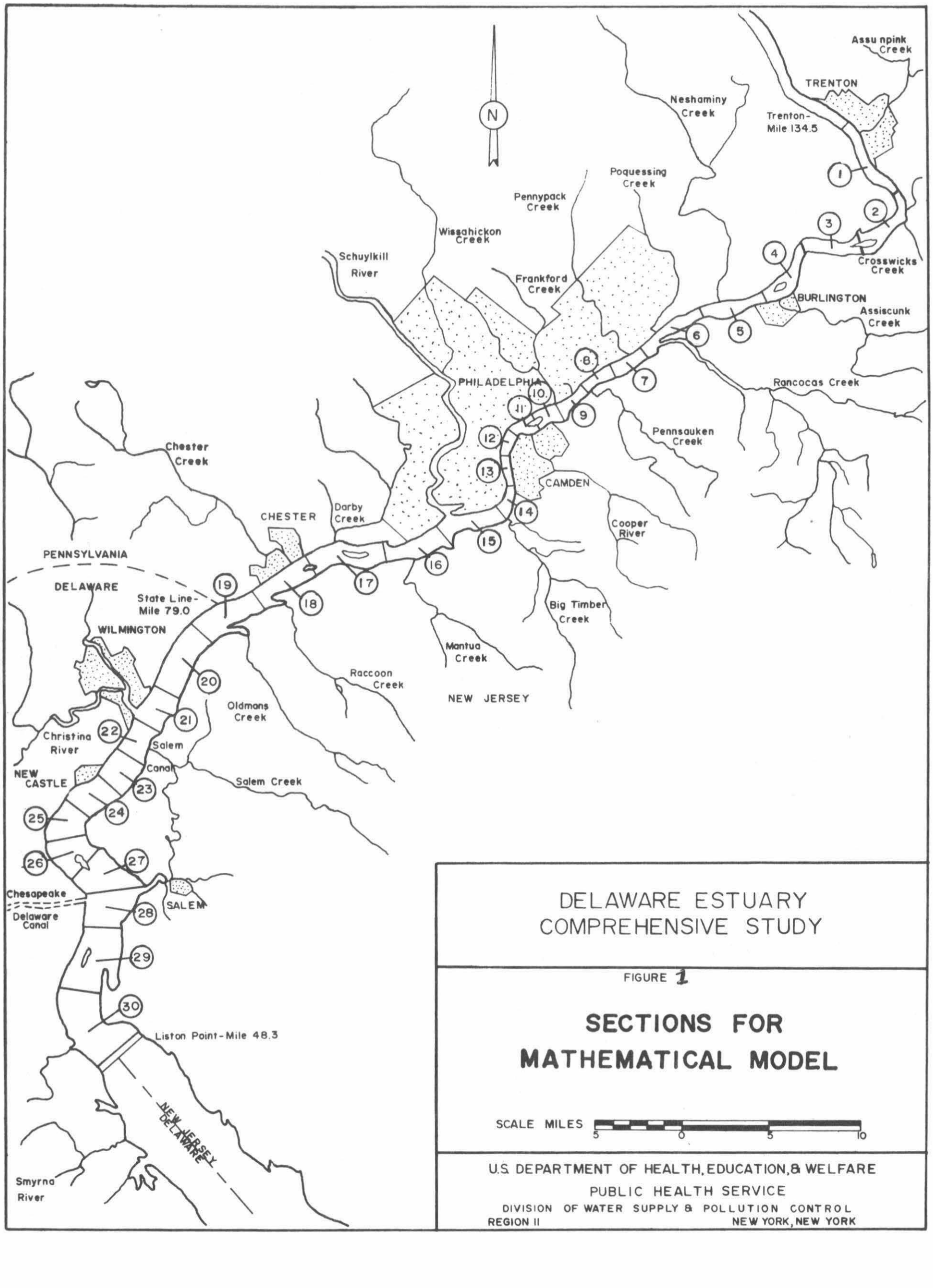
[1] "Mathematical Model for Dissolved Oxygen" by Robert V. Thomann, Jour. San. Engr. Div., ASCE, Vol. 89, No. SA5, Oct., 1963.



DELAWARE ESTUARY
COMPREHENSIVE STUDY

FIGURE 1

SECTIONS FOR MATHEMATICAL MODEL

U.S. DEPARTMENT OF HEALTH, EDUCATION, & WELFARE
PUBLIC HEALTH SERVICE
DIVISION OF WATER SUPPLY & POLLUTION CONTROL
REGION II NEW YORK, NEW YORK

the long-term forecasting. This includes estimates of the effects of waste removal on water quality. The DO was chosen as the primary indicator variable to describe the level of water quality in the estuary. A number of verification analyses have been carried out on the Delaware. These analyses compare the observed DO longitudinal and temporal variations with the concentrations computed by the mathematical model. In general, the comparisons have been quite good indicating that the model is a sufficiently accurate representation of the environment.

Given an adequate computational procedure to describe cause and effect relationships for the Delaware, the next step was to orient thinking toward the water quality control problem.

There are three central points to consider in almost any engineering control problem: 1) the ability to predict the consequences of certain control actions (the DO model indicated above), 2) an expression of the goals; here, in terms of water use or water quality and 3) reasonably good estimates of the costs and benefits of the goals that are being investigated. To assist the DECS on the latter two points, a unique committee structure was established.

DECS Advisory Committee Structure

Three advisory committees were formed to aid the DECS in matters of policy, technical assistance and water use. Membership of the Policy Advisory Committee (PAC) includes personnel from State, Interstate, and Federal Agencies which have legal power to abate pollution. Other agencies with related interests in the field of water resources are invited to attend meeting as guests.

The functions of this committee are to:

- A. Attain consent among the states on pollution abatement policy and plans and assure full coordination of effort and understanding.
- B. Coordinate and assist in the inclusion of established water pollution control plans in the over-all comprehensive water pollution control plan.
- C. Relate the Study to possible interim procedures for pollution abatement.
- D. Advise the Federal Water Pollution Control Administration relative to the present DECS and future studies involving water pollution control in the estuary.

Membership of the Technical Advisory Committee (TAC) includes personnel familiar with the technical aspects of water pollution control from agencies participating in the work of the Study.

The functions of this committee are to:

- A. Keep agencies represented apprised of the status of the DECS - in this manner the agency has one of its personnel who has a complete understanding of the technical phases of the DECS.
- B. Assist the Federal Water Pollution Control Administration in planning and coordinating the DECS.
- C. Provide technical assistance:
    1. in the organizing of various projects
    2. by providing additional qualified personnel for special phases of the Study

3. by reviewing preliminary drafts of reports by advising the PAC and the Water Use Committee on technical matters

Formation of the Water Use Advisory Committee (WUAC) required a procedure different from that of the other two. In reviewing the nature of the Basin, it was decided to form four subcommittees: 1) Recreation, Conservation, Fish and Wildlife; 2) General Public; 3) Industry; and 4) Local Governments and Planning Agencies.

Ninety organizations were invited to the initial meetings. At the second meeting each subcommittee elected a Chairman who also would represent the subcommittee on the parent WUAC.

Functions of the WUAC are to:

A. Indicate the needs and desires of the people of the estuary relative to water use with water quality as a criterion.

B. Act as a public relations group.

C. Assist in special non-technical phases of the DECS.

It is interesting to note that, from the original three committees, there are now 17 such committees or work groups (see Table 1). Presently participating through the committees are: three State water pollution control agencies, one interstate agency, three Federal agencies, nine cities, 12 planning agencies, 30 civic organizations, and 45 industries for a total of 103. The 103 organizations provide over 200 participants on the various committees. It is this group then that has the primary responsibility for advising the DECS on meaningful water use and water quality objectives.

TABLE 1

DELAWARE ESTUARY COMPREHENSIVE STUDY

Committee Structure (as of February 1965)

- 1 I. Policy Advisory Committee

- 2 II. Technical Advisory Committee
  - Subcommittees
    - 3 A. Industry
    - 4 B. Fish and Wildlife

- 5 III. Water Use Advisory Committee
  - Subcommittees
    - 6 A. Recreation, Conservation, Fish & Wildlife
    - 7 B. General Public
    - 8 C. Local Government and Planning Agencies
    - 9 D. Industry
      - Work Groups
        - 10 a. Chemical
        - 11 b. Electrical Utilities
        - 12 c. Food
        - 13 d. Paper
        - 14 e. Petroleum
        - 15 f. Steel
        - 16 g. Manufacturers' Associations
        - 17 h. Miscellaneous

Alternative Water Quality Control Procedures

Thus, the basic approach utilized by the DECS is to ensure that the policy, technical and water use interests all play a role in the decision-making function. In order for this approach to be successful, adequate information must be available on the various alternatives to accomplish a given goal. Several different routes are being explored by the DECS. These include the control procedure of requiring equal per cent removal of wastes by all sources, designated the Uniform Treatment approach. In contrast to this, the mathematical model was imbedded in a linear programming formulation to answer the following question:

What combination of waste removal will meet a given DO goal at a minimum overall cost to the region?

The results from the answer to this question provide an optimum (in the sense of least cost) solution to attain the given DO goal. However, the solutions indicate that the program in general would be extremely difficult to implement. Table 2 illustrates this point. The least cost solution for a 2 mg/l goal indicates that waste source #3 should remain at present levels while waste source #5 should go to total removal of waste. This is a consequence of the interaction of cost, location along the estuary and waste to be removed. The total cost for the Uniform Treatment (2 mg/l) solution was almost twice that of the least cost. Information of the type shown in Table 2 is continually being made available to the Advisory Committees of the DECS to arrive at meaningful decisions pended on an examination of a number of alternatives.

Research Needs

The above investigations indicated several areas for

TABLE 2*

EXAMPLES OF COST SOLUTIONS FOR THE DELAWARE ESTUARY

Type of Cost Solution		Least		Uniform Treatment	
To obtain a DO level of		2 mg/l		2 mg/l	
Waste Source	Present Treatment	Cost $\$.10^6$	Treatment	Cost $\$.10^6$	Treatment
1	Secondary	-	Secondary	0	Secondary
2	Primary	0.2	Secondary	0.1	Intermediate
3	None	-	None	0.6	Intermediate
4	Primary	-	Primary	3.9	Intermediate
5	Primary	1.2	Total Removal	0.5	Intermediate
-	-	-	-	-	"
-	-	-	-	-	"
-	-	-	-	-	"

NOTE: Flow, diffusion, reaeration and decay coefficients are the same for all conditions.

* From a draft of a preliminary study.

additional research. Most important among these research areas is the need for considerably more information in the benefits of water quality improvement. This includes research into adequate analytical methodology for the evaluation of such nebulous benefits as increased real estate valuation, and aesthetic values as a function of quality. Also, additional data are needed on the effects of quality on recreation, sport and commercial fishing, and the costs of municipal and industrial water treatment.

Research is needed into the possible institutional arrangements that might be necessary to carry out more efficient programs if they indeed are feasible from a sociopolitical point of view.

The alternative programs described above are based on a steady-state (static) analyses of the environment although the mathematical model itself is a dynamic representation. The investigation of optimally attaining a given time-varying objective would be particularly appropriate as various large scale water quality management systems begin to operate.

Finally, more research is needed in the interactions and feedbacks in the physical environment including the effects of quality changes in the biological regime and the interrelationships between various quality parameters such as toxic substances and DO on the fish and wildlife of a given area.

MULTIDISCIPLINARY RESEARCH ON AN ESTUARINE ENGINEERING PROJECT

by

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INTRODUCTION

Other participants of this conference have considered, in stimulating fashion, various problems concerned with development of adequate methods for using and conserving water resources. All seem to agree that every effort must be expended to establish and employ the soundest decision-making procedures possible. Clearly, the setting of goals for water resource-use programs must be placed on an objective, practical, scientific basis. Thus, the latest technique of Systems Analysis or Operations Research should be utilized to achieve the most satisfactory evaluations and arrays of recommended decisions in the least possible time.

Dr. Thomann pointed out that to make the Systems Analysis approach work in water resources management, several types of reliable information are needed. Among those suggested by him and Dr. Sherwani are psychological, sociological, and political data to facilitate establishment of meaningful, adequate goals and these must be accompanied by more adequate economic data and engineering evaluations and more significant data about the resources themselves. Limitations of knowledge in any of these areas place constraints on the efficacy of the results of Systems Analysis and consequently on the choices offered decision makers.

I concur in this evaluation. Increased resource-oriented psychological and sociological research is necessary. We <u>must</u> establish valid scientific bases for setting goals for resource management programs and these can only be in the psychological and sociological requirements of humans. One cannot help wondering why this necessity is not, even yet, adequately recognized by state and federal governments, which support most resource research.

Though economic evaluations are the most easily made, continuing economic research is needed. In making forecasts, economic studies must be accurate and include realistic appraisals of all uses to which resources are and can be put, including aesthetic applications. Otherwise, value judgments will continue to be inadequate.

Especially critical is the lack of knowledge about structure and dynamics, and the inherent requirements and limitations of the natural resources we seek to manage. Often ignorance in this area is so pervasive as to prevent recognition of problems (costs) likely to develop if water resources are utilized in a particular manner, for example, if a vast construction job such as deepening of an entire tidal river or establishment of a large number of reservoirs throughout a large watershed is carried out. To make realistic value judgments, we must recognize all present and future problems. For every problem unrecognized the likelihood of a wrong choice or untoward result increases. Cost-benefit ratios can only be as good as the costs and benefits considered.

To date, development of resource systems, for example, river basins, has proceeded in piecemeal fashion with resource-use plans and construction of projects and legislative and executive regulations promulgated in provincial, myopic fashion. As these developments have increased in number, magnitude and complexity, cries of anguish from areas, persons, communities or industries whose desires and activities were adversely affected, and the ensuing conflicts waged at every level and with every weapon imaginable, have forcefully indicated the complex nature of these resource systems and the complex and often conflicting needs, desires and goals of the users.

DIFFICULTIES OF SCIENTIFIC MANAGEMENT OF WATER RESOURCES

It is not always possible to wait until one can decide from a vantage point of complete, and completely reliable, information from all fields to make resource-use decisions. Society's needs are often urgent. Therefore, many, or even most, decisions will be based on imperfect knowledge. However, it is important to know the limiting essentials, whatever they are, and have as much detail as possible.

It is important to recognize that the amount of detail that specialists must unearth or develop is dictated by the intricacies of the problems presented to them by decision-makers.

The problem of necessary detail may be quite troublesome in ways other than in setting limits on the efficacy of decisions. It can affect the relationships between scientists and managerial groups, who wonder why scientists do not know more. For example, in discussions of problems with these groups, it is not unusual for scientists to be asked, plaintively, "Why don't you already have the information we are asking for? You've been working on it for over 20 years!" Usually, reasonable examination discloses that early work was either poorly supported or was satisfactory to the simpler problems of the time.

Other difficulties arise to trouble both managers and scientists -- often inapplicable or inconsequential questions asked in the past led to inadequate results. It is easier to ask productive questions about resources when the phenomenon under study is understood. It is in this context that wide-ranging basic research studies generally prove especially valuable in resource problems because they provide information which enables scientists to focus on the real problems quickly.

Also quite serious and equally frustrating to scientists and managers alike is the lack of stability in the resource systems under scrutiny. Changes in resource systems, some slow and some rapid, are caused by: 1) natural, progressive or regressive evolutions, 2) natural random fluctuations, 3) changes brought about by increasing use by society, and 4) changes brought about by varying uses by society. For example, the tidal James is no longer the same as it was when the current, large-scale field and laboratory studies involved in VIMS' Operation James River (discussed below) were begun in the early spring of 1964, only two short years ago. Changes have been wrought on the structure and the dynamics of the James by such factors as increased contamination, severe and long-lasting droughts, major depth changes in the Hampton Roads area by harbor dredging, alteration of freshwater input by increasing freshwater withdrawals and diversions, and increasing wetland destruction. This changeability makes it difficult to evaluate the reliability and significance of information more than a few months old. Many resource scientists would like, for quite obvious reasons, to see a moratorium established on man-made alterations within the system under study while detailed scientific studies are going on -- obviously an impossible dream. Fortunately, there are techniques of compensating for these changes, for example, by developing and utilizing scale and mathematical modeling capabilities.

As society's awareness of the problems has grown, more enlightened efforts to solve them have evolved. Increasingly, but still far too slowly, the tremendous power and capability of Science and Technology are being brought to bear in Resource Management efforts -- Prometheus, the giant, is being unchained.

RESOURCE INFORMATION NECESSARY

Data from many fields are necessary to proper evaluation, planning and management of natural resources. Of greatest importance is the necessity to have basic, accurate information about the potentials of the natural resources, themselves. Without information concerning the nature, requirements and limitations of the resources being considered, management's plans and regulations for development, exploitation and conservation of natural resources may be ineffectual -- even detrimental. It can be categorically stated that management activities which ignore the basic nature of the resources, themselves, are unlikely to succeed except through happenstance. Hence, there is great need for accurate information about the chemical, biological, geological, and physical nature of our important resource systems, but these are quite often complex and difficult to study. Let us consider the James River as a specific example of complexity and discuss the role of natural and man-made interactions.

The James River Basin, Virginia's largest and most valuable aquatic resource system, offers an excellent example of a natural resource system under pressure of development by many interests, some of which are actually or potentially destructive or in conflict. Clearly, it is an inherently complicated system and can be used to illustrate many facets of the difficulties involved in management of water resources. The tidal James is now under close scrutiny of a determined, multidisciplined study on some of its mysteries -- a scientific assault for the purpose of developing information useful to those faced with making the decision on channel deepening.

THE JAMES RIVER BASIN

The James River system is composed of two major segments: 1) that portion above the fall line at Richmond (the Upland region) (tributaries entering below Richmond are ignored) and 2) that below the fall line (the Tidewater region), see Fig. 1. Though quite complex themselves, the freshwater montane and piedmont portions comprising the Upland are simpler in structure and dynamics than those of Tidewater. Tidewater James is, itself, divisible into two, or three parts -- depending on how far seaward one wishes to follow the system. These parts are: 1) the fresh-tidal, 2) the estuarine, and 3) the coastal. Structurally and dynamically, each part is different, the parts interact, and the boundaries of each are mobile, moving inland and seaward in response to tidal cycles and variations in river flows and bottom and shoreline geometry.

To illustrate the differences between these different reaches of the James, we might assume the roles of riverside observers examining the river from various vantage points from above Richmond to Hampton Roads. Looking out over the James at Bremo Bluff, we would see that the water flows one way, downstream. We would, therefore, decide that wastes dumped into this portion of the James would be carried away by the rapidly moving fresh water. We would be right, of course, but downstream users would suffer if our wastes had not been handled properly.

Another observer looking at the James at Curles Neck would also note that, with the exception of the ebb and flow of the tides, the fresh water has a net downstream flow. As

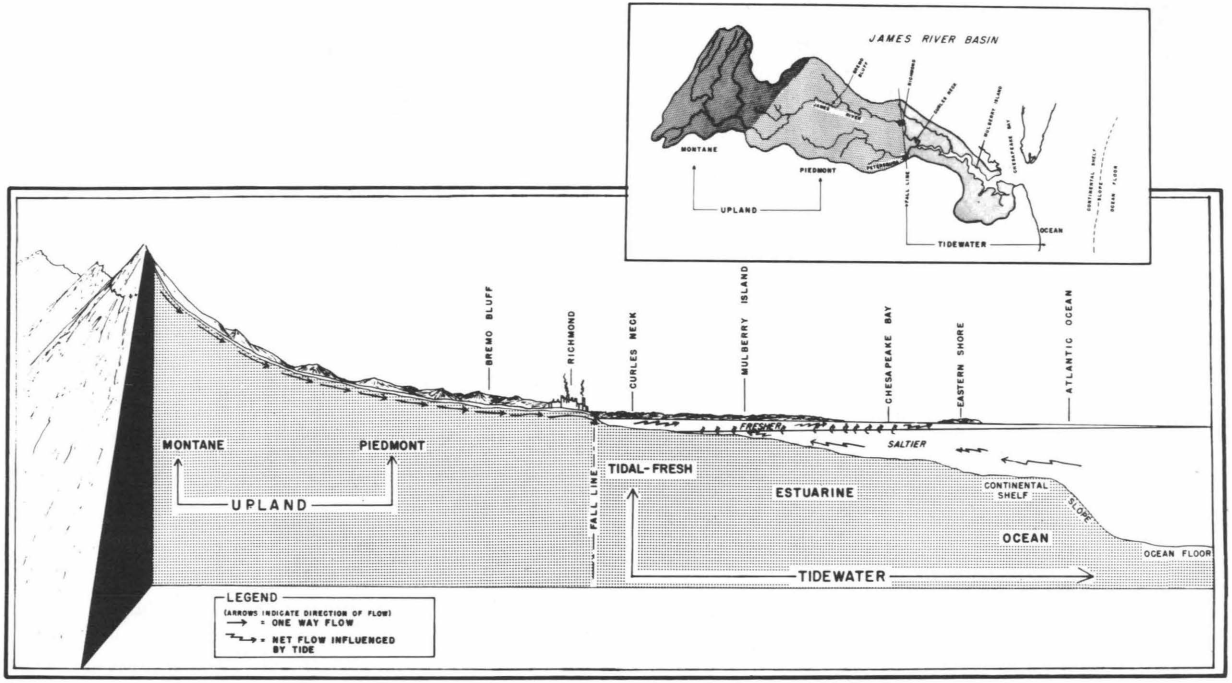

Fig. 1. The James River Basin showing regions, parts and places mentioned in text. Diagrammatic representation depicts the flow characteristics of the different parts of the Upland and Tidewater region. (Courtesy of U.S. Waterways Experiment Station, Vicksburg, Mississippi.)

a result, he might conclude that wastes dumped into this section of the river would be carried away. He might further conclude that a considerable volume of waste could be handled by the obviously vast quantities of water in this tidal reach. In both conclusions he would only be partially correct. Tidal oscillations slow the process of transport considerably and wastes tend to oscillate back and forth with the tide. For this reason, the value of the vast quantities of water in mixing and carrying away wastes is reduced because dilution and dispersion are not as rapid as in a one-way system and downstream movement is slow. For example, during periods of low, freshwater discharges a month or more may be required to transport wastes thirty to forty miles. As a result, it is not as difficult as it would seem to overload an estuary. The upper tidal portions of the James and Potomac offer excellent examples of overloading with wastes.

We move downstream to Carter's Grove or Mulberry Island and again look out over the estuarine portion of the James. Here the James is vast -- millions upon millions of gallons of water. Again the water exposed to view has a net downstream flow. Surely one might think that wastes discharged here would cause no problems but would be diluted swiftly by the great quantities of water and carried away by the net downstream movement. However, in this we could be very wrong. Not only do tidal oscillations slow the movement of water as at Curles Neck but here the James is usually two-layered, really two streams, one under the other. The uppermost system or layer is fresher and lighter and has a net flow downstream; the lower system is saltier and heavier and has a net <u>flow upstream</u>. Thus, wastes introduced into this lower layer would not go downstream but have a net flow upstream. It is this two-layered system that raises especial difficulties with the proposed Tidewater projects.

The James River Navigation Project

As an example of the complex factors involved, we can examine the long considered James River Navigation Project which many in Virginia hold to be an highly desirable developmental project intended to enable deep draft vessels to reach farther inland with greater loads and hence improve the economics of shipping to inland areas. Probably a more important economic objective is the possible opening of the James to increasing industrialization.

This project will deepen the channel from its present 25-foot depth to 35 feet, from the James River Bridge, just above Hampton Roads, to Richmond, some 98 statute miles inland.

In 1955, when the project was first seriously proposed, few objections were raised. Later, on realization of the close relationship between the structure and dynamics of the upstream-flowing, salt layer in the estuarine portion and the 1) successful setting and survival of oyster larvae, and 2) successful survival and growth of oyster spat in the river, a new economic factor was introduced. According to the latest and most widely held ideas, the bulk of the oyster larvae contributing to the successful seed areas in the James are spawned in Hampton Roads and are carried upstream in the salt layer where they set on shell piles in the traditional seed areas above the James River Bridge off Mulberry Island (Fig. 1). In these seed areas the spat, as oysters are called after setting, survive and grow to seed size because predators and diseases are controlled by low salinity.

As a result of relatively recent studies of the circulation of estuarine and coastal waters, it became apparent to estuarine scientists that the water in the lower salt layer has a net upstream movement and that this current carries larvae of many other animals to their setting areas. It was also clear from long-term observations that survival of oyster spat on the seed beds is due to restriction of the activities of oyster predators and diseases by the low salinities prevailing in these areas. Further, it is evident that changes in the structure and dynamics of the estuarine portion will result from alterations in the density differences normally existing between the fresher layer (originating upstream) and the saltier layer (originating in the ocean). In an estuary like the James, which is an horizontally stratified but partially mixed estuary, an increase in the volume of salt water, a certain result of dredging, will increase stratification, reduce mixing between the two layers and increase the distance upstream that salt water of a particular concentration intrudes. It also will reduce the rate of flow of the upstream moving current in the lower layer. These modifications could reduce the setting and survival of seed oysters in an area on which, in normal years, the major portion of the oyster industry of Virginia is directly dependent for most (70 to 80 per cent) of its seed. The resulting change in production of seed oysters and probable reduction in the productivity of the oyster industry could cause an economic loss of sizable proportions to the Commonwealth and constitute a significant project cost.

Though many factors undoubtedly played strong roles in the decision, Virginia officially decided to delay approval of the James River Navigation Project until a scientific study could be carried out to determine the effects of channel modification on the oyster industry. The General Assembly of 1964, appropriated funds and ordered the Commission of Fisheries to conduct the necessary research and report on the relationships between the channel deepening as proposed and seed oyster production in the James estuary.

Operation James River

In order to comply with this legislative directive, the Commission of Fisheries contracted with the Virginia Institute of Marine Science to plan and carry out the studies and make the analyses. In turn, VIMS designed and initiated a comprehensive research project involving cooperation between scientific disciplines and engineering technologies. This research project, called Operation James River (OJR), began with an analysis of the problem (accomplished in 1963) and will end with a report to the General Assembly and Governor in 1967. A much more comprehensive technical report embodying all of the vast amount of scientific data produced by OJR will be presented to the scientific community later.

Since the ultimate problem revolved around setting and survival of oyster larvae and spat, the interactions between oysters and their important biological associates and the physical characteristics of their environment were considered initially.

For an area to qualify as a good seed-producing area, the following conditions are necessary:

1) Adequate brood stock must be present.
2) Oyster larvae (spawn) must be able to survive and develop to setting stage.
3) Larvae must be transported from spawning to setting areas.
4) Larvae must encounter suitable substrate for setting at the propitious time in their life history.
5) Larvae must be able to set and enter spat phase.

6) Spat must survive and develop into seed.

7) Seed should be free of diseases and suitable for transplanting to growing areas.

Survival and development of parental stocks and oyster larvae and spat depend upon the suitability of a number of physical and biological factors such as 1) currents adequate to transport larvae, 2) satisfactory food, 3) suitable salinity, temperature and dissolved oxygen, 4) adequate cultch suitably located, and 5) relative freedom of larvae and spat from predators and disease organisms.

In order to determine whether the proposed James River Navigation Project would have an adverse effect on oyster seed production, it was considered necessary that all of these factors be examined.

Thus, the large-scale operation, OJR, was designed to secure information concerning the interaction between the physical attributes of the estuary such as 1) surface and subsurface currents, 2) lateral and vertical movements of water masses, 3) salinity, 4) temperature, 5)geometry, 6) light, and 7) other factors; and biological activities such as 1) the spawning of oysters, 2) the transport and survival of oyster larvae, and 3) the setting, survival and condition of spat or seed. Important corollary information has also been sought on sedimentation, on spatial and temporal distribution and abundance of plankton, bottom organisms, predators and disease organisms of oysters and on dispersal and diffusion of actual and possible contaminants of all types.

The operation has been carried out in five phases. Order of priority of these phases was determined by the time requirements of each phase; for example, the time required in construction and verification and testing of an hydraulic model made it necessary to secure the prototype data for model design (data from the river, itself) as quickly as possible in 1964.

Larvae and spat, predators and diseases have special times to spawn, set, migrate, reproduce and infect. These, often rigidly timed, biological events imposed rigid scheduling limitations on the work.

Accordingly, the operation was planned and is being carried out in five programs. These are:

A. Compilation of Existing Data

Accumulation, evaluation and analysis of all existing physical and biological data about the James (and other pertinent estuaries) and the important animals and plants therein was begun in 1963 and is continuing. Considerable information has been unearthed and new insights into biological and physical processes in the James estuary are developing.

B. Physical Studies of the Estuary

Careful examination of the present physical factors operating in the estuary are underway or completed. These have involved:

1. Regular physico-ecological cruises of the estuary studying temperature, salinity and oxygen at several critical places. These cruises have been underway since March of 1964 and many of their data have been summarized.
2. Special studies designed to examine different critical areas and special aspects of the dynamics of the estuary were planned and executed. These involved:

a. Occupation of stations arranged to study dynamics of currents, salinities and temperatures over extended periods of time.

b. Completion of extensive transects designed to show the relations between channel and shoal waters at critical areas like Wreck, White and Brown shoals.

c. Dye studies (using Rhodamine B and fluorometric analytical equipment) to follow currents and movement and dispersal of dye-tagged water masses.

3. Surveys to gather data to be used in construction and verification of the hydraulic model and in other modeling techniques have been conducted, completed and transmitted to the Hydraulics Division of the U.S. Army Engineers, Waterways Experiment Station at Vicksburg, Mississippi. These studies involved as many as nine boats and 40 men and considerable equipment. As a result of these field surveys, extensive and valuable data have been gathered which will not only be useful in the model work but in evaluating older theories of structure and dynamics of the estuary.

C. Physical Studies in the Laboratory (scale model)

In order to permit controlled evaluations of the effects of the channel deepening on the distribution of isohalines (areas of equal salinity) and the structure and dynamics of the tidal James under various conditions, an hydraulic model of the tidal James has been designed, constructed and verified and will soon be in experimental use.

This facility will allow us to vary conditions of river flow, salinity, channel depth and position, siltation and contamination and, above all, achieve predictability of dynamic structure and function of the estuary.

D. Biological Studies in the Estuary

A partial list of specific biological investigations being carried out is:

1. Spatial and temporal distribution of oyster spat in the estuary.
2. Spatial and temporal distribution of oyster and analogous larvae.
3. Location of primary parental or brood stocks (sources of spawn) for James seed area.
4. Spatial and temporal distribution of oyster drills (a predator) and their effects on spat and adult oysters.
5. Spatial and temporal distribution of MSX and *Dermocystidium* (diseases) and their effects on spat, seed and adult oysters.
6. Spatial and temporal distribution of plant and animal plankton.
7. Spatial and temporal distribution of bottom organisms.
8. Spatial and temporal distribution of young and adult fishes and crabs (other important marine and estuarine species).

These studies have been designed to show not only the seasonality, numbers and distribution of the organisms involved but also to disclose relationships of these factors to salinity, currents, oxygen, etc. All phases are underway at this time,

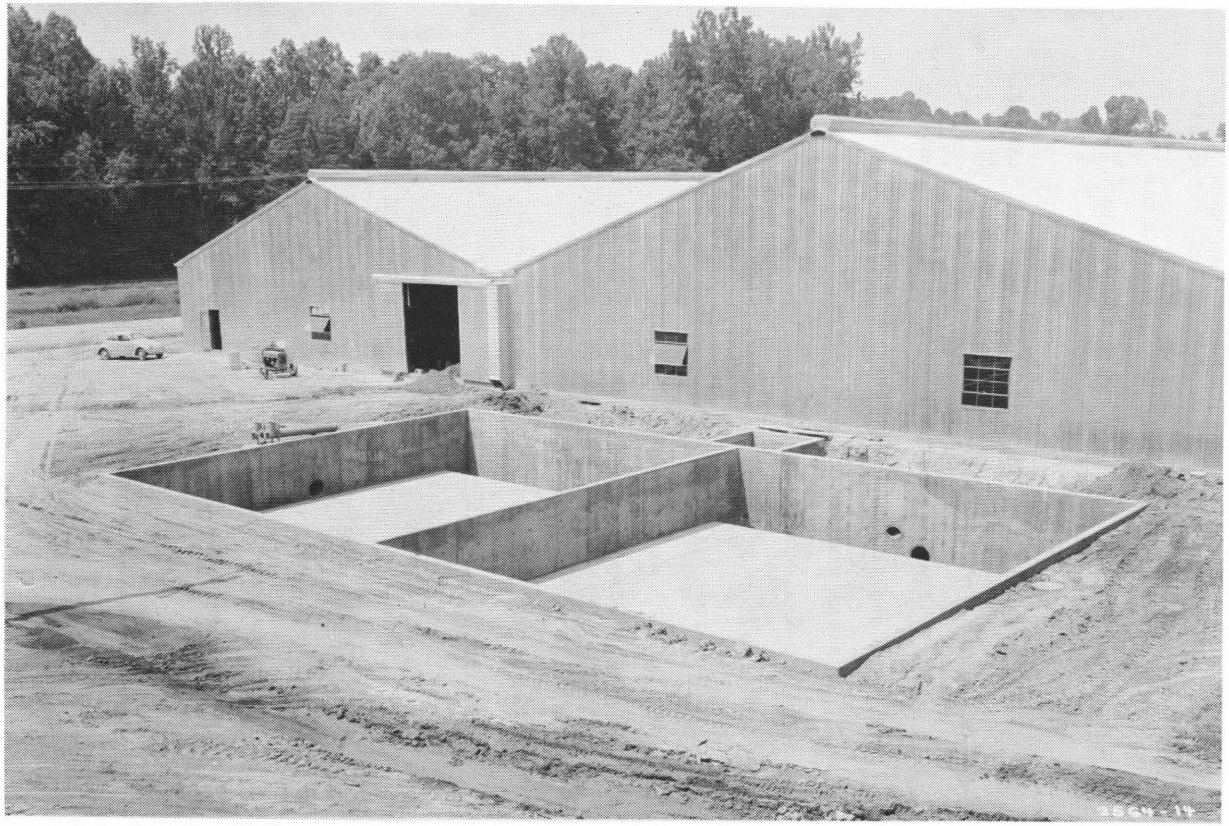

Fig. 2. Showing building housing the James River hydraulic model and the water supply facility. (Courtesy of U.S. Waterways Experiment Station, Vicksburg, Mississippi.)

Fig. 3. James River hydraulic model showing two different stages of construction. (Courtesy of U.S. Waterways Experiment Station, Vicksburg, Mississippi.)

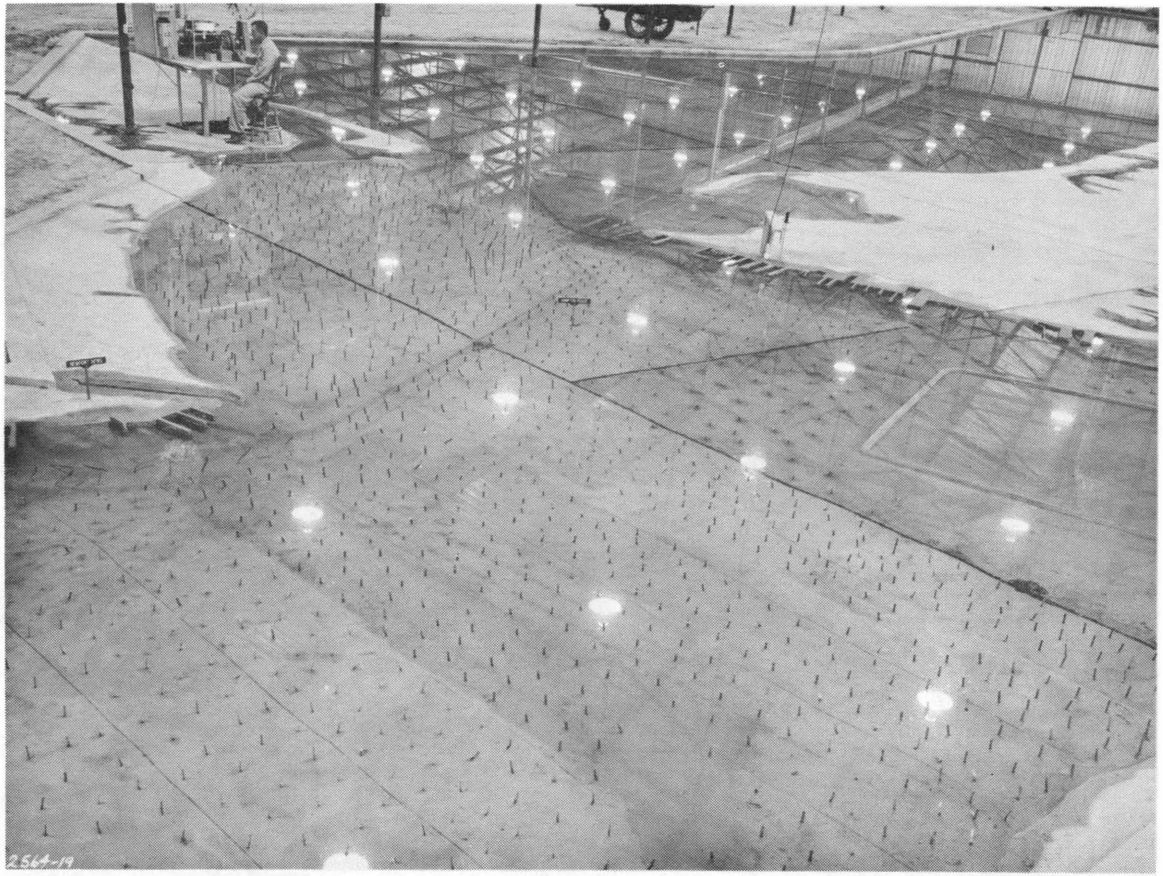

Fig. 4. James River hydraulic model showing Hampton Roads (looking seaward) with Newport News on the left and Norfolk on right. (Note Craney Island Disposal Area intruding on right and tidal programmer upper left.) (Courtesy of U.S. Waterways Experiment Station, Vicksburg, Mississippi.)

Fig. 5. James River Hydraulic Model looking upriver from Hampton Roads to seed beds above James River Bridge in center foreground. (Dark spots on bottom are adjustable roughness simulators and resistance units. Reserve fleet included in center background.) (Courtesy of U.S. Waterways Experiment Station, Vicksburg, Mississippi.)

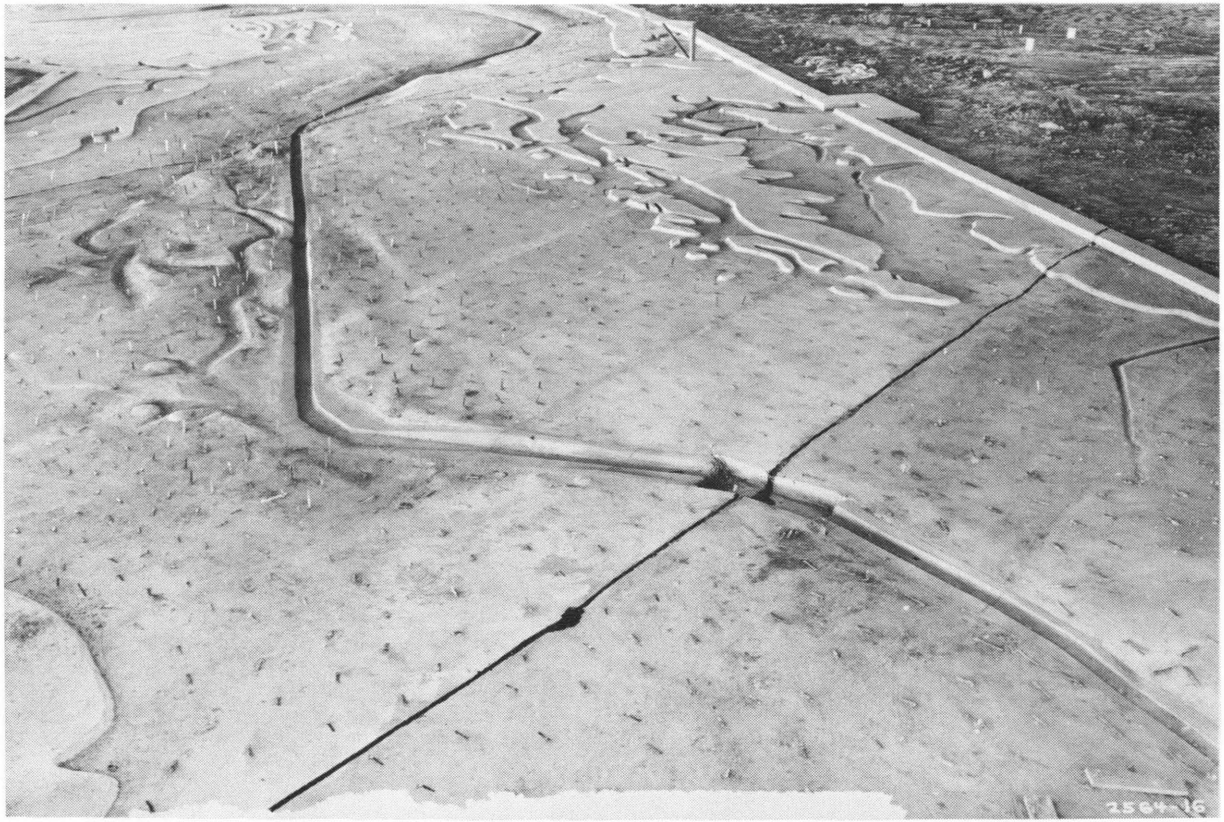

Fig. 6. James River hydraulic model showing Rocklanding Shoal Channel Reach, off Mulberry Island, without water. Model channel is dredged by removing molded channel blocks. (Courtesy of U.S. Waterways Experiment Station, Vicksburg, Mississippi.)

with greatest emphasis on those pertaining directly to oyster larvae and spat, their food, predators and diseases.

E. Biological Studies in the Laboratory

In order to better establish the relationship between oyster larvae, spat, drills and other predators and diseases and competitors and analogous larvae, carefully designed controlled studies of their responses to the various environmental variables, e.g., salinity, temperature, light, oxygen, currents, are being carried out in the laboratory. Some of these studies are underway and will be terminated in the fall.

From these studies we expect to be able to give a much more accurate appraisal of the impact of the proposed James River Navigation Project and succeeding engineering or industrial projects on the biota of the estuary. A very valuable bonus will be the improved understanding of the physical and biological environment of the tidal James.

SUMMARY

As a result of earlier work, the James is now a classic in marine science. When Operation James River, a massive, multidisciplinary study, is completed, the James will be one of the best known estuaries in the world. Furthermore, we will be in a much better position to study and evaluate the effects of increased 1) industrial and domestic wastes, 2) siltation, 3) river flow alterations, 4) wetlands destruction and other man-made changes on the intended use of this natural resource. The data will be much more adequate for use in Systems Analysis or Operations Research procedures. In addition, the data and conclusions will be available to those responsible for decisions which will result in the fuller utilization of this great but not limitless resource for the maximum benefit of our present and future society. In view of the importance of the James River Basin to Virginia, significant advantages should accrue.

BIOGRAPHICAL SKETCHES

CARL W. ALLEN - Dr. Allen is Professor of Economics in the School of Business at Virginia Polytechnic Institute. His undergraduate and graduate work was at the University of Kentucky and Iowa State University. He has done considerable work in the area of agricultural economics and published extensively in this field.

EMIL J. GUMBEL - Dr. Gumbel did his undergraduate and graduate work at the University of Munich. He has had teaching assignments at the University of Heidelberg, the University of Paris, the University of Lyon in Europe as well as Newark College, Brooklyn College, and Columbia University in the United States. At various times, he has been a consultant to the National Bureau of Standards and Stanford University. In 1952 he was a Guggenheim fellow. Dr. Gumbel has written more than 300 articles and enjoys an international reputation for his work on the statistics of extreme values.

WILLIAM G. HARGIS - Dr. Hargis, in addition to being Director of the Virginia Institute of Marine Science, serves as Chairman of the Department of Marine Science at the University of Virginia and Dean of Marine Science at William and Mary. His academic achievements include a B.A. and M.A. from the University of Richmond and a Ph.D. from Florida State University. His research endeavors include 39 technical papers mainly in areas of biological oceanography, biology of monogenea, systematics, and phylogeny.

RICHARD G. KRUTCHKOFF - Dr. Krutchkoff is an Associate Professor of Statistics at Virginia Polytechnic Institute. His undergraduate and graduate work was at Columbia University, New York. Since graduation in 1964, his research has resulted in 13 publications. Professional memberships include nine scientific and mathematical societies.

JABBAR K. SHERWANI - Dr. Sherwani is a native of Pakistan and earned his initial degree of B.S. in Civil Engineering at the University of Punjab. Since coming to the United States, he has acquired a M.C.E. from the Polytechnic Institute of Brooklyn, a Ph.D. in Groundwater Hydrology at the University of Utah, and M.P.H. in Water Resources Economics at Harvard University. His past professional positions include: Deputy Chief, Water and Power Section, Planning Commission, Pakistan; and Consultant, White House Panel on Waterlogging and Salinity in West Pakistan.

ROBERT V. THOMANN - Dr. Thomann obtained a B.S. in Civil Engineering from Manhattan College in 1956 and his Ph.D. in Oceanography and Meteorology from New York University in 1963. His professional life has been with the U. S. Public Health Service where he worked on the water quality studies of the Connecticut and Delaware Rivers. He also worked as engineer in charge of the Narragansett Bay Hurricane Barrier Study and is presently Technical Director of the Comprehensive Study being done on the Delaware Estuary. Dr. Thomann is the author of several technical papers on simulation studies using mathematical models.

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