MULTIDISCIPLINARY RESEARCH IN THE GREAT LAKES BASIN

U of M
Sea Grant Program
NOAA

A PROGRESS REPORT ON MATHEMATICAL MODELS FOR NATURAL RESOURCE SYSTEMS ANALYSIS

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A COOPERATIVE RESEARCH PROGRAM SPONSORED BY THE UNIVERSITY OF MICHIGAN AND

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TABLE OF CONTENTS

INTRODUCTION AND SUMMARY

As illustrated in Figure 1, the research program can be identified as falling into five general subject areas--aquatic ecosystems, hydrology, land use, sociopolitical impacts, and technological impacts. Each subject area is then identified according to (a) field- and discipline-oriented studies which emphasize identification, description, and explanation of processes; and (b) mathematical modelling studies which are intended to explain and predict joint behavior of interrelated processes. The mathematical modelling studies incorporate data and relationships from several subject areas and therefore perform an integrative function.

A higher level of integration of research findings and activities occurs when results from broad subject areas are pulled together in the form of a gaming simulation and a man-computer interactive graphic simulator (called ECOS) shown in the center of Figure 1. The two simulations serve different purposes as well as having common educational and training objectives. The gaming simulation is intended to serve a training function demonstrating: (a) the value of and need for cooperation among political jurisdictions in management of natural resources, (b) the unexpected and counter-intuitive effects that can accrue from uninformed attempts at managing a complex entity such as a large aquatic resource, and (c) the need for looking ahead as well as looking back when setting policy and making environmental decisions. ECOS is an advanced man-computer interactive system for constructing models of complex multi-variable biological systems such as an aquatic ecosystem.

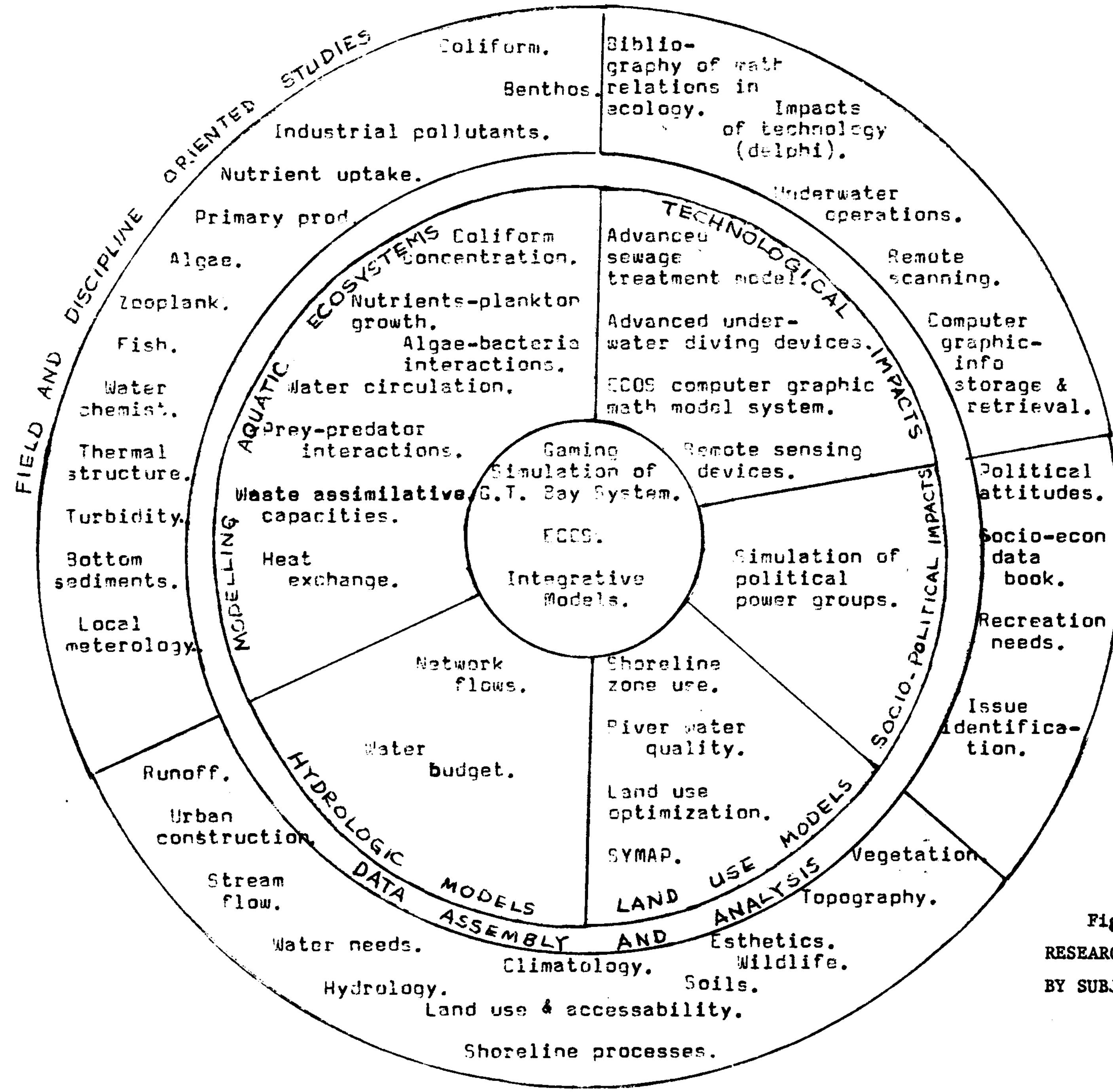


Figure 1
RESEARCH PROGRAM
BY SUBJECT AREAS

The research program on Sea Grant can also be seen from the perspective of study objectives in contrast to the subject area and integrative function viewpoint. The difference in these points of view lies in the explicitness with which one specifies an ultimate functional purpose attached to the investigation. The advantages of this viewpoint are the ability to differentiate among projects as to when end results have been attained, the nature of the end results, a more or less explicit statement of the use or disposition of the end results, and how end results logically tie together. (Roughly speaking the level of integration of study objectives increases as one proceeds down the left-hand column of Table A.) From this specification of study objectives one can identify those integrative points at which inter-institutional cooperation is needed and should be sought.

The relationship between an environmentally-oriented, University-staffed, research project and a unit of government, such as a city, county, or multi-county authority, can develop from the initiative being exercised at either end. The governmental unit may initiate a request for assistance, as in the case of the shorelands zoning project, or the need for creation of an inter-institutional arrangement for environmental management may be first identified by members of the research team. In either case the development and implementation of any type of management plan involving a University research team cannot take place without close participation and agreement by officials of the area for which the plan is being developed.

The two main objectives of the aquatic ecosystem modelling program are: (a) to anticipate or predict environmental extremes which may be counter-intuitive or unanticipated and which arise from a combination of

STUDY OBJECTIVE	OUTPUT	EXAMPLE	DISPOSITION
development of devices or practices	new or improved devices and procedures; surveys	underwater habitats; remote sensing	dissemination of specifications; manuals
contribution to knowledge in pure or applied science	new findings; hypotheses, relationships	industrial source of pollution; heat exchange; water circulation	technical report; recommendations to legislators; planners, executives
demonstration of relevance or feasibility of math and computer models to cope with resource problems	computerized multivariable models of physical, chemical, biological, urban, economic processes	nutrient assimilative capacity of bay waters; preferred patterns of land use	technical report; recommendation for further use of technique
demonstration of procedures and tools for managing and planning for multiple use resources at inter-institutional level	computerized multiple process simulation using man/man and man/machine interactive capability	gaming simulation of multiple-jurisdictional lands and waters around Grand Traverse Bay	training managers, legislators, and planners w/r to environmental management; identification of preferred policies
development and implementation of resource management plans at interinstitutional level	development of mode of operation among jurisdictions; management options and responses	shorelands zone plans	recommendations for zoning

SEA GRANT FROM A STUDY OBJECTIVE PERSPECTIVE

TABLE A

environmental practices, demands for water use, and natural forces; and (b) to determine the capacities of an aquatic ecosystem for absorbing a variety of waste products.

The information needed to build a predictive model of an aquatic ecosystem is general circulation patterns, flow and concentrations of tributaries and direct discharges for all quality variables of interest (monthly or weekly averages), and field observations for model verification. A compartmental model is a standard method for handling spatial gradients which should be verified using a nonreactive (conservative) substance. Rates, accumulations, and conversion coefficients are of main interest in model construction and the discipline-oriented field studies contribute to the estimation of these quantities.

Progress has been made on every model shown in Figure 1. In some cases working models are presently available in preliminary form. Field data have been utilized in model verification but not all field data will be used in predictive model building. Measurements of trace metal concentrations, for example, are taken to identify whether a problem is present rather than to model its paths of uptake. Table B summarizes the steps in construction and use of physically interpretable mathematical models of environmental systems.

In terms of general conclusions it is evident that there is no such thing as a single model that can provide answers to man's and nature's intervention upon our natural resources. The basic difficulties in predictive model building in which one attempts to anticipate critical environmental conditions, i.e., the "problems" rather than "answers to a problem," are to initially present the proper "settings" and to build

Identification

Physical, chemical, or biological species; sources and sinks for energy and materials; compartments; pathways of movement

Parameter Estimation

Spatial distributions and gradients; normal or background concentrations; input, output, and transfer rates of materials and energy

Quantities Explained or Predicted

Assimilative capacities; residence times; environmental extremes or conditions of imbalance; trends in species composition

Action Responses to Model Exercises

Field surveillance; contingency plans for fast response to crises; land use plans and policies; regulated waste treatment and disposal; greater cooperation and awareness of public officials in setting legal standards

BROAD STEPS IN MODEL CONSTRUCTION

TABLE B

into the model a capability to exhibit a variety of histories in response to different natural or man-made interventions. A system model acts in an integrative capacity pulling together knowledge and data from numerous disciplines and will identify the joint use of a variety of different field measurements. System models will not be used to develop and implement environmental management plans unless they have the understanding, acceptance, and hopefully participation of responsible individuals for whom the plan serves.

SCOPE OF THE MODELLING PROGRAM

The societal-oriented objective of the research program sponsored by the University of Michigan Sea Grant Program is to determine the consequences of alternative courses of action aimed at development of water and land resources of the Great Lakes and then to present this knowledge to interested and responsible citizens. Following this broad objective an interdisciplinary program of studies has been undertaken which is organized around the concept of a predictive capability to "anticipate" the impact upon parts of the natural environment of a range of actions that might be undertaken by man.

The subject matter of the studies has been divided into four areas--aquatic ecosystems, land utilization, socioeconomic-political impacts, and technological impacts as shown in Figure 1. Within each area are basically two interrelated activities which are quantitative modelling and discipline-oriented field studies. Both activities are initially descriptive in their basic output. However, each of these activities should produce explanatory and normative statements in the form of recommendations for, or priorities on, courses of action to be taken by legislative or administrative agencies.

Many questions arise in the formulation and development of an interdisciplinary program with rather broadly interpretable objectives. Among these are relevance of individual studies, funding priorities, overlap of effort, communications among workers, education benefits, administration, evolution of program concept, and reports of findings.

The purpose of this report is to review the objectives and progress of the quantitative modelling activities within the aquatic ecosystems and land utilization sectors and to include a discussion of related field studies viewed in a supportive context. As stated above, conclusions and recommendations are expected from discipline-oriented studies apart from their function of providing data inputs to modelling activities, but this aspect of the field studies is not discussed in this report.

Model Use As An Aid To Decision Making

Quantitative models have been used in the private sector to assist the human decision-making process principally through the application of operations research. The application of quantitative modelling as a direct input to decision making in areas affecting renewable natural resources, however, has been much slower except possibly in problems regarding water distribution and treatment. One can cite several reasons for this lag which are of a technical, economic, political, and perceptual nature. Technically, models involving biological and chemical processes have suffered from a lack of tested theoretical descriptions. Moreover, mass balance equations do not incorporate the administrators' preception of a problem sufficiently well to serve any useful purpose in the line management of natural resource systems. It has also been the case that some scientists tend to get bogged down feeling the need to take account in a model for all perceived causes and effects without considering their relative contribution to total change. The usefulness of first-order approximations as aids to decision making tends to get discounted as a result.

Experience in the application of operations research has shown that a very few factors operating in a complex process account for most of its behavior. Scientists working in disciplines have been quite observant of multiple interacting processes but as a matter of method have concentrated upon identifying and explaining narrow sections with one result being that they have not become conversant with methods for dealing explicitly with networks of processes.

The economic consequences of decisions affecting the future development, use, and maintenance of the natural resources of a region are of the utmost importance. While the demand and supply of natural resources for various uses, and descriptive input-output analyses of dollar flows have been the subjects of much quantitative study, the critical questions now are the following: What is the economic impact to local government and private citizens of policies and regulations dealing with pollution control and the preservation of renewable natural resources? Should a multiple use natural resource, limited in amount, be allocated in response to the demand for the different uses? The factors of resource ownership, and economic and political power of the groups competing for the resources are critical in analyzing these questions. One seeks to determine in what manner environmental protection regulations are going to affect future resource ownership and what this will mean in terms of financial income to both the public and private sectors at the local level.

Recent economic studies of aquatic resource systems have attempted to develop normative models that allocate costs or maximize total output among a limited group of aquatic resource users. Others have dealt with economics of water and sewage treatment plant location and designs and operating rules for water treatment plants. One difficulty in accepting these normative models as authoritative has been differences in opinion over what constitutes realistic economic or resource use optimization criteria. Another difficulty has been a lack of confidence in the model "solutions" due to inadequate data used to estimate parameters required by the model. Meanwhile, decisions affecting aquatic resources and local economies continue to be made across the United States based upon little or no reliance upon quantitative predictive analyses of outcomes of different courses of action. Decision makers have employed models in the form of patterns of thinking in much the same way as scientists. Models in the form of diagrams, formulas, and various kinds of tables are a standard part of the decision maker's tool kit. Therefore, the question is not whether the legislator, forest manager, city planner, or county commissioner can use models effectively, but how the computerized model of a complex ecosystem should be adapted to meet the needs of these and other decision makers.

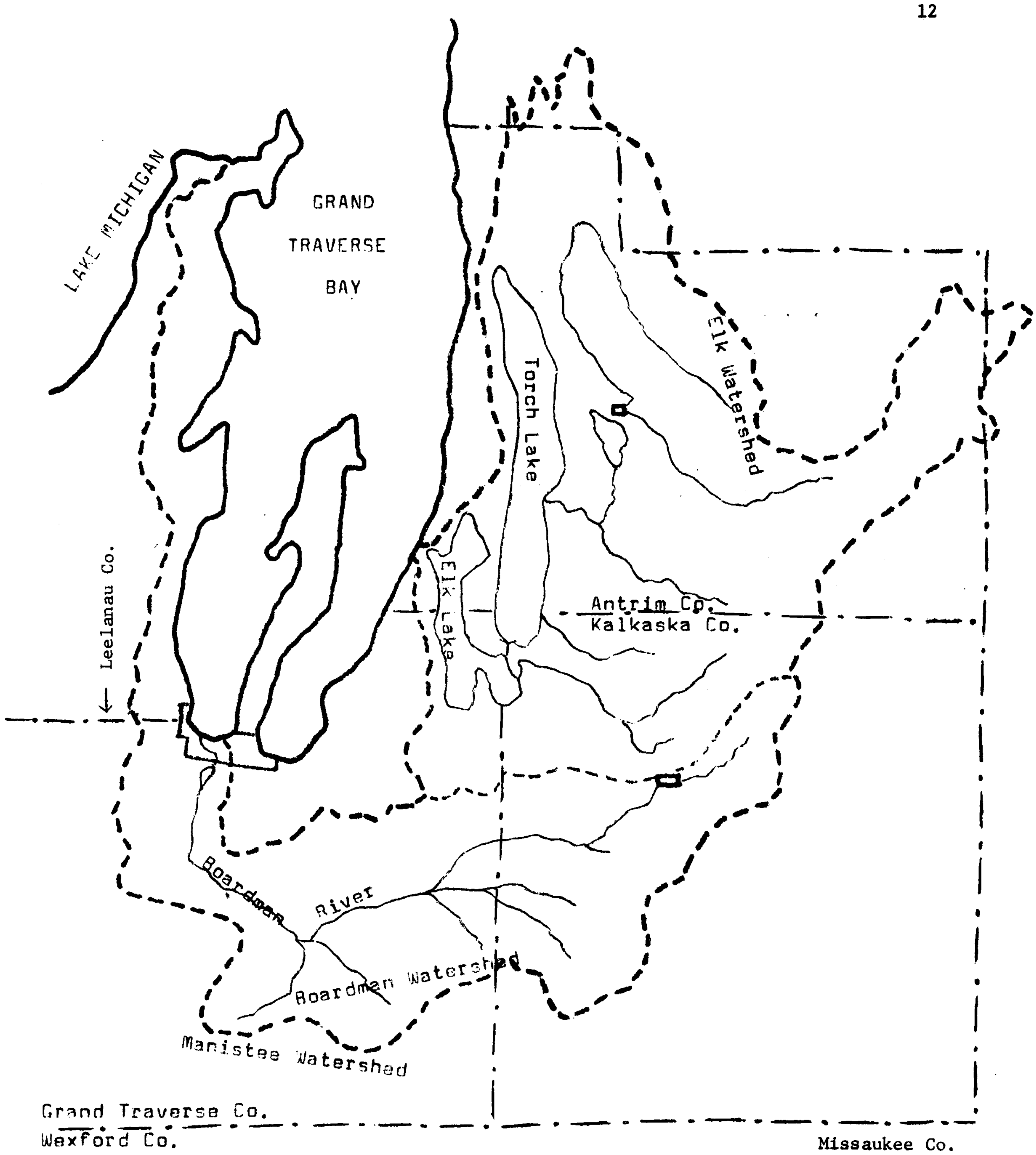
Faced with the problems of communicating with various pressure groups in both the public and private sector and responding to problems often requiring immediate action, the decision maker is usually not in a position to be concerned with the technical complexities of computerized models. It is the task of a technical staff suitably located and in touch with the decision maker to inform him of optional courses of action in anticipation of a range of problems that the decision maker himself may foresee. Above all, the decision maker requires options because he must make responsible decisions. A technical staff exercising a model of interlocking, environmentally sensitive, physical, chemical, and biological processes should be able to provide these options together with their projected impacts.

The Grand Traverse Bay System

As shown in Figure 1, the field studies and modelling activities are divided into five sectors entitled Aquatic Ecosystem, Land Use, Socio-Economic - Political Impacts, Technical Impacts, and Hydrology. These sectors are perceived to describe an entity called the "Grand Traverse Bay System." The natural boundaries of the system are defined so as to contain the waters of Grand Traverse Bay, bottom sediments sufficient to include the interstitial layer and all layers subject to scouring action by currents, the flora, fauna, surface waters, and soils contained in and on the surrounding watershed as delineated by Figure 2. Superimposed upon the natural scene is man with his artifacts and impacts which are reflected in the sectors shown in Figure 1.

Aquatic Ecosystems

The sector entitled Aquatic Ecosystem represents physical, chemical, and biological processes occurring in the waters of Grand Traverse Bay proper. It is an open system biologically, chemically, and physically as well as energetically. Physical inputs are received in the form of water (from precipitation, Lake Michigan, surface runoff, and fifteen to twenty streams from the surounding watershed), solids in various forms (silt, organic materials, bottom sediments, animal and human wastes), gaseous substances, and unreactive compounds. Chemical inputs are received from a variety of sources including streams, septic tanks, surface runoff, storm sewers, treated and untreated waste discharges, gases, and direct dumping. Exogenous sources for biological species received by the bay waters are Lake Michigan, watershed streams, wildlife, storm sewer discharges, and



GRAND TRAVERSE BAY WATERSHED

Figure 2

human contacts. Exogenous energy sources for bay processes are wind, sunlight, gravity, water movements from Lake Michigan into the bay, heat, energy stored in biomass entering the bay, and various man-made energy inputs.

Within the physical confines of the bay complex interactive processes of change are occurring with respect to its physical, chemical, and biological conditions which are viewed as responses to the exogenous energy and materials inputs. By representing mathematically certain key characteristics, conditions, or "states" of the bay as they respond to or undergo change with respect to both materials and energy inputs, one can project the states through time to obtain a conditional forecast of bay conditions at any future point in time. When forecasting by means of mathematical models one must be careful to distinguish between behavior which is due to the model construction itself and behavior which arises from the real system or process under study. One must also realize that as the forecast lead time increases the degree of conditioning of the forecast must also increase, thereby subjecting the forecast to additional uncertainty (see Figure 3).

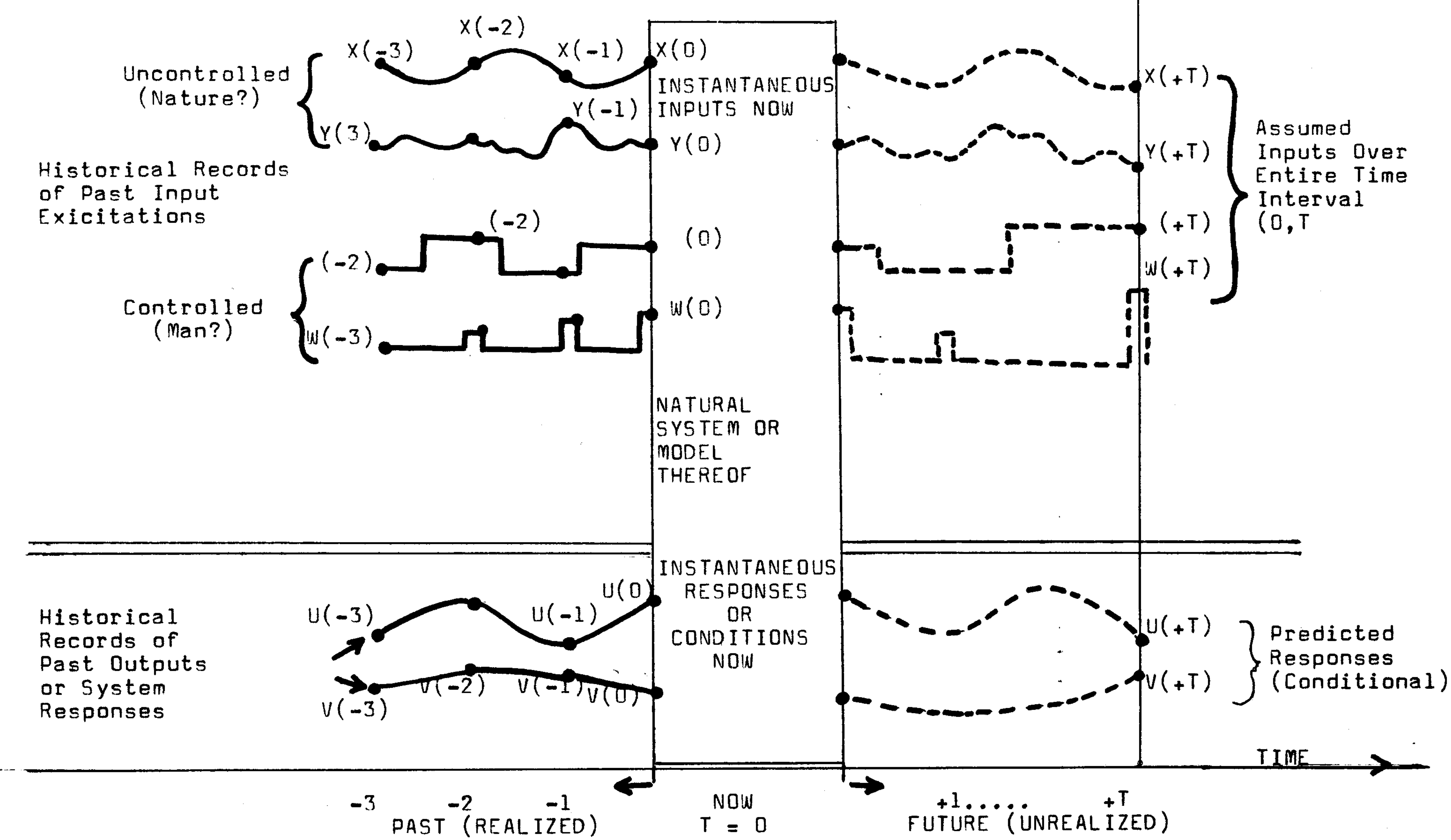
Land Use

The land use section is not concerned with modelling a terrestrial ecosystem at the same complexity as with the waters of Grand Traverse Bay. Instead, it deals with questions of planning of land uses consistent with the natural (topographic, soil, vegetation, wildlife) capabilities of the land and the projected impact upon the natural environment of patterns of land use if implemented, including the waters within the region covered. The models entitled "shoreline zone use" and "Boardman River Water Quality" are mainly descriptive but are complimentary with the latter serving to

FIGURE 3

Schematic Representation of Past, Present, Future

States of a Natural System



evaluate the ecological effects of "preferred" mixtures of land uses within delineated zones along the river. The land use optimization model is normative in that the output is the assignment of sites to uses over a region in such a way that an objective function is optimized. The criteria may be economic, political feasibility, or compatability of uses with nearby sites.

Aquatic Ecosystem Modelling Objectives

The modelling work reviewed in this sector covers physical, chemical, and biological processes linked by means of dynamic and steady-state materials balance equations that purport to describe an aquatic ecosystem. When coupled, these mathematical representations define a simulation of chemical and biological responses of an aquatic ecosystem to a variety of natural and man-made "inputs" or "excitations" including responsive behavior of a food chain (see Figure 4) to a variety of such inputs. In particular one seeks to predict transport rates, accumulations, and the disposition of selected physical, chemical, and biological materials through an open network of (physical, chemical, and biological) "cells" that depict the ecosystem. By a variation of inputs one seeks to identify or anticipate "crisis" conditions in the environment outside of which natural biological balances will not be maintained. Such conditions are called environmental tolerance limits and an important function of the model as described below is to anticipate crisis conditions that have a reasonable probability of occurrence in the future so that an attempt can be made to avoid such extremes.

An example of the tolerance limits of an aquatic ecosystem being exceeded resulting in an explosive and destructive disturbance of its biological balance occurred in Lake Apopka in south central Florida.

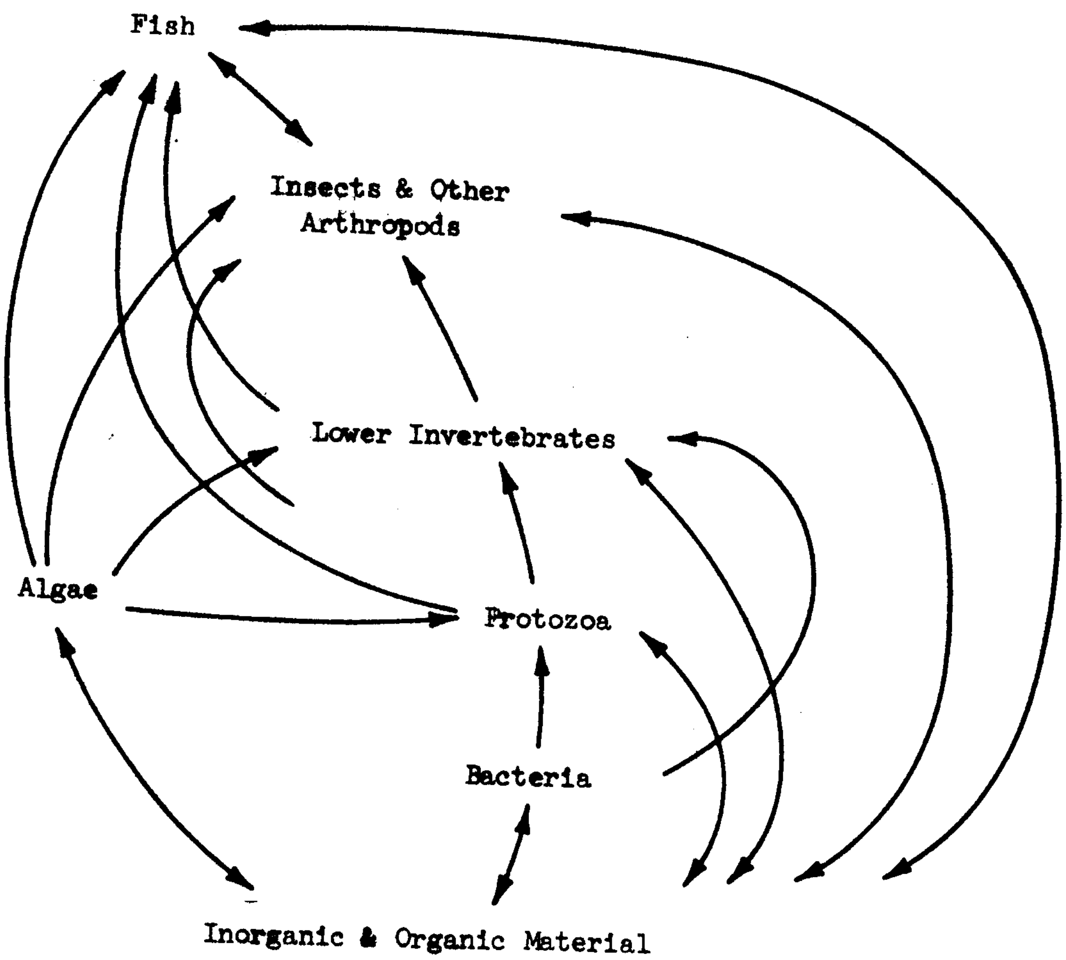


Figure 4 Simplified food web.

A state agency decided to lower the lake level by draining off water. As a result of this drainage the water temperature rose, oxygen was depleted, and a certain bacteria began to undergo rapid growth. Large quantities of alligators, birds, turtles and fish died enmass and even humans were reported to have contracted the organism.

By means of exercise of the model in an anticipatory or predictive mode one hopes to estimate nature's own tolerance limits by examining the impacts upon biological and chemical balances resulting from changes in temperature, oxygen, available light, alkalinity or other environmental parameters. One also seeks to determine assimilative capacities of an aquatic ecosystem for waste products arising from industrial, recreational, or other activities of man. These questions are generally of the "what if" variety which requires forecasting a set of "responses" or conditions describing an aquatic environment over an extended interval of time. Thus, the forecasts are necessarily conditional upon assumptions that are made about the inputs over this period.

When speaking of crisis conditions in a natural system brought about by an extreme perturbation of some combination of physical, chemical, or biological conditions one is concerned here with the estimation of nature's tolerance limits rather than questions of economic, political, or sociological crises resulting from the upsetting of natural balances. For example, natural flooding by a river may cause economic and even sociological tolerance limits to be exceeded but it does not necessarily cause permanent imbalance to an aquatic ecosystem.

With regard to the establishment of legal limits on the "quality" of wastes emitted to the natural environment, one is reminded of the difference between legal limits set by man on the quality of effluents fed back to the environment and natural environmental tolerance limits outside of which chemical and biological balances will not be maintained. It has been stated that one aims to estimate natural environmental tolerance through the exercise of an ecosystem model. It should then be possible to infer realistic legal limits on the quality of discarded waste by exercise of the mathematical model. This is an application related to, but not equivalent to, estimating natural environmental tolerance limits.

Moreover, the "scientific input" to the establishment of water quality standards has been mainly that of expert judgment in which experts attempt to estimate "normal" variations in environmental conditions within which natural balances will continue to exist. What a carefully constructed mathematical model of a natural system can do that the human mind cannot do is simultaneously juggle many variables and parameters to estimate their joint effects over a broad range of hypothesized conditions. It permits the legislator, administrator, or scientific expert to systematically compare and evaluate the probable impact of several alternative legal limits on the quantity and quality of waste products. It also permits a comparison of the likely results of different treatments designed to correct a problem.

From an examination of several possible futures of an aquatic ecosystem, each responding to a different set of inputs which are man-made as well as nature-imposed, one hopes to produce a set of scientifically determined options to "management" that will be helpful at the very least in avoiding those heretofore unpredictable and disastrous consequences for an aquatic environment. Optimistically speaking, it will identify the most effective course of action in the environmental protective sense subject to a set of economic and human consumptive constraints.

Examples of lake pollution problems in which scientific models would no doubt have been useful in predicting outcomes of optional treatments have occurred in Lakes Apopka (Florida), Tahoe (California), and Washington (Washington). It is hoped that the modelling experience obtained here will be instrumental in establishing a model of Lake Michigan as an aquatic ecosystem together with parts of its surrounding watershed.

Present, Past and Future in a Model

Figure 3 depicts in a somewhat abstract fashion a set of inputs to a "system" (such as an aquatic ecosystem) which force a set of responses (variables describing significant system conditions or behavior) through the workings of a set of interacting processes (represented by the shaded box in Figure 3). Such processes constitute the connecting links between inputs and outputs and are represented by mathematical equations. The inputs and outputs are set within a time frame denoted by past, present (now), and future to clarify the concepts of instantaneous response versus a prediction or forecast of a future response, and to distinguish between cases where one must make assumptions about inputs in order to estimate a response, as opposed to using known historical information in order to estimate a response. In general, it is impossible to estimate future behavior of a system output unless assumptions in some form are made regarding the inputs. The particular form and degree of explicitness of these assumptions about the inputs depend upon the method of prediction (the system model). On the other hand, if one wishes to estimate or describe by means of a model an instantaneous or immediate response (regarded as the present or now) as opposed to a future response, then for all realistic situations one need make no assumptions about the future behavior of the inputs because the future is not involved in the outputs. At most one needs a record of the present values of the inputs together with their past values which are assumed to be given as part of a known record. For certain limited types of models most or even all of the past record is unnecessary for estimating the immediate output.

Models of Biological Production

The principle followed in the construction of the dynamic models describing what are regarded to be the key indicators of chemical and biological change in the bay is the law of conservation of mass:

(net accumulation of species i in cell j) = (A) - (B) + (C) - (D) (1)

(weight/time)

where

(A) = net transport of species i into cell j due to convection, dispersion, sedimentation, or other means from endogenous cells or exogenous sources.

(weight/time)

(B) = net transport of species i out of cell j by convection, dispersion, sedimentation, or other means to endogenous cells or exogenous sinks.

(weight/time)

(C) = net generation of species i within cell j by growth or other mechanisms.

(weight/time)

(D) = net consumption of species i within cell j by respiration, predation, uptake, precipitation or other mechanisms.

(weight/time)

Distributions in biomass concentrations with depth or in lateral directions can be handled mathematically in terms of "homogeneous" cells or by the use of partial differential equations. The approach taken here is the former in which a single cell is first considered, to be later extended to several cells. The exact number will depend upon water circulation in the bay at different seasons of the year. Note that factors (A) and (B) above incorporate circulation effects and hence exogenous energy inputs that force circulation such as wind, currents from Lake Michigan, and the Boardman River. Factors (A) and (B) also reflect biological effects (C) and (D) since part of the biomass transported out of a cell is determined from (C) and (D). Table 1 contains a listing of the variables that are taken into account in a simple model of biological production. Exogenous variables may be independently controlled either in tabular or function form and act as forcing inputs. Endogenous variables are those which interact among themselves and with exogenous variables to provide indicators of water quality and biological production. Those endogenous biological variables labeled predators x, y, and p represent production at levels in the food chain shown in Figure 4 lying above algae and bacteria.

That is, the differential equations describing the production levels within the food chain contain sufficient generality to represent different species of fish, insects, or lower invertebrates in different simulation runs. Individual differences are represented by saturation constants, specific growth rates, and stoichiometric coefficients. The symbols (F) and (L) appearing after each designated variable are being measured in the field (F) or are being controlled in laboratory (L) experimentation, or both (F,L). The symbol (M) indicates that a variable can be simulated by a model. Thus, an exogenous variable symbolized by (F,M) can be represented by either a function or in

Exogenous Variables

Physical Inputs

1. Time
2. Temperature (F,L,M)
3. Water Circulation (F,M)
   a) Wind (F,M)
   b) Stream Flow (F,M)
   c) Lake Michigan Currents (F,M)
   d) Dispersion Coefficients (F,M)
4. Sunlight (F,L,M)
5. Transparency (F,L,M)

Chemical Inputs

1. Nitrogen (F,M)
2. Phosphorus (F,M)
3. Organic Carbon (B.O.D.) (F,M)

Biological Inputs

1. Coliform Bacteria (F,M)

Endogenous Variables

Chemical Response

1. pH (F,L)
2. Oxygen (F,L,M)
3. CO_2 (L,M)
4. Organic Carbon (B.O.D.) (F,L,M)
5. Alkalinity (F,L)
6. Phosphorus (F,L,M)
7. Nitrogen (F,L,M)

Biological Response

1. Bacteria (L,M)
2. Algae (F,L,M)
3. Predator x (F,L,M)
4. Predator y (F,M)
5. Predator p (F,M)

VARIABLES INCLUDED IN BIOLOGICAL PRODUCTION MODELS

Table 1

tabularized form resulting from field measurements. A variable which is followed by all three symbols (F,L,M) has been measured in the field, is being controlled in laboratory validation, and is a model prediction. Tables 2 and 3 contain a further breakdown of the variables listed in Table 1 according to the particular model with which they are associated. Note that the model entitled "biological production" and "algal-bacterial" models represent the lower parts of the food chain shown in Figure 4.

The intended functions of these models are to predict productivity in bay waters as a response to excitations, to determine factors limiting eutrophication, to forecast the disposition of materials that exist in bay waters, and to estimate assimilative capacities of bay waters for wastes. When the multicell models are completed an estimate of the changing distribution of biomass in bay waters can be obtained from which one can predict the existence of pockets of high biomass of chemical concentrations. Reference (1) contains a detailed description of the present state of development of the models listed in Tables 2 and 3 except for the coliform model.

Those variables labeled "exogenous" in Table 1 and which are followed by the symbol "M" can be represented as inputs into equation (1) above as predictive output of another model, i.e., in function form.

For example, nitrogen, phosphorus, and B.O.D. (source of organic carbon) are variables which are modelled as measures of stream quality as part of the Boardman River Water Quality model. Sunlight intensity is a variable predicted by a formula developed as part of the local meteorology subproject and is represented within the model entitled "Heat Budget." (See reference (2) for a development of this formula.) Water

Inputs:	Prey-Predator	Algal-Bacterial	Coliform	Biological Production
Parameters:				
Time	x	x	x	x
pH	x			x
Temperature	x	x	x	x
Water Circ.	x	x	x	x
Stream Flow	x	x	x	x
Sunlight		x		x
Oxygen	x			x
CO_2				x
Coliform dieoff rate			x	
Alkalinity		x		
Nutrients:				
Dissolved Nitrogen	x	x		x
Dissolved Phosphorus	x	x		x
Organic Carbon (B.O.D.)	x	x		x
Biological Concentrations:				
Bacteria	x	x		x
Algae		x		x
Coliform			x	
Predator x	x			x
Predator y				x
Predator p				x

Model: (spanning the model columns)

VARIABLES CONSIDERED IN MODELS OF BIOLOGICAL PRODUCTION

Table 2

Outputs:	Prey-Predator	Algal-Bacterial	Coliform	Biological Production
Parameters:				
pH		x		x
Oxygen		x		x
CO_2		x		x
Organic Carbon	x	x		x
Biological Concentrations:				
Bacteria	x	x		x
Algae		x		x
Coliform			x	
Predator x	x			x
Predator y				x
Predator p				x
Nutrients				
Nitrogen				x
Phosphorus				x
Organic Carbon	x	x		x

VARIABLES CONSIDERED IN MODELS OF BIOLOGICAL PRODUCTION

Table 3

transparency is related to available light at any given depth below the surface of a column of water and is thus being modelled indirectly as available light [1,p20] in the models of biological production.

Water circulation includes convective and dispersive transport effects both of which are represented in terms (A) and (B) of equation (1). Currents at different depths are being measured by moored current meters over extended intervals of time at the approximate positions shown in Figure 5 as well as by drogues which are tracked as they move with currents. These measurements will be used to estimate parameters in a computerized model of water circulation that covers the entire Grand Traverse Bay and from which circulation rates needed in terms (A) and (B) of equation (1) will be computed. Current measurements are highly important in that they provide data necessary to estimate the rate at which given volumes of water are being cleansed of solid-liquid wastes or conversely are being contaminated with the same materials.

Nitrogen and phosphorus have been introduced into laboratory tests associated with model validation as ammonia and orthophosphate which are simplifications of the phosphorous and nitrogen cycles (see Figures 6 and 7). It is expected that more detailed representations of the interactions of these nutrients with bacteria, algae, and higher consumers will be incorporated into the model at a later date. The forms in which phosphorus and nitrogen are being measured in Grand Traverse Bay include ammonia, nitrite, total dissolved nitrogen, total nitrogen, total dissolved phosphorus, and total phosphorus. It will therefore be possible to check more elaborate models of the nitrogen and phosphorous cycles against field measurements. Biological oxygen demand is also included in bacterial and algal growth dynamics which is labelled as organic carbon in Table 1.

A controlled experimental program is being planned in which the effects of various combinations of phosphates, nitrates, silica, and organic carbon upon the growth of phytoplankton and zooplankton are to be analyzed. The purpose is to develop a more accurate predictive equation for growth of these species in the presence of different combinations of the compounds mentioned above. The experimental design is presently under development but it is expected that the underlying model will be a nonlinear regression of growth rate upon concentrations of phosphate, nitrate, silica, and organic carbon. This experimental program supplements a more modest laboratory experimental program in which phosphate, nitrate, and organic carbon (but not silica) are controlled so as to determine their effects upon bacterial and algal growth.

Determination of Assimilative Capacities

The term "assimilative capacities" is used in the plural because a body of water assimilates substances at different rates. For example, chlorides are conserved while phosphates move through a cycle as shown in Figure 7. The assimilative capacity for phosphorus is determined by the rate at which compounds of phosphorus are converted into "slowly available" or "very slowly available" forms. It is clear that the assimilative capacity of Grand Traverse Bay for water soluble compounds of phosphorus (and other reactive chemical compounds) can be defined relative to a number of different human uses. Each use is tied to permissable concentrations of substances (plant growth, uptake of poisons by fish, etc.) that are products of the reactions generated by the wastes being assimilated. By inclusion of the appropriate sinks into which reactive waste compounds are distributed and by including purifying mechanisms such as re-aeration, one can in fact use the models of biological production to estimate assimilative capacities.

Coliform Bacteria

A predictive model for total coliform bacterial concentration has been developed which presently applies to the extreme lower end of the west arm of the bay, offshore from Traverse City. There are several inputs to the model including rate of coliform discharge to bay waters due to septic tank and industrial waste discharges, circulation from other parts of the bay, boating releases, and wildlife production. A number of parameters, including temperature, die-off rates, and coliform production rates are included so that, for example, it should be possible to predict the ultimate effects of large-scale shifts from septic tank sewage treatment to centralized collection of sewage by a sanitary sewer system. The model, as presently developed, does not predict gradients which would be most pronounced offshore from bathing beaches and areas where industrial and municipal wastes are discharged. A least-squares fit of the nonlinear model to daily readings of coliform concentration collected at the municipal water intake during 1963 was performed using a gradient search technique and an excellent fit of the data to the six parameter model was obtained. This represents a demonstration of the feasibility of developing dynamic models for accurate short-term predictions of concentrations of species undergoing biological decay. The method should be applicable to the prediction of concentrations of chemical species in solution which decay over time.

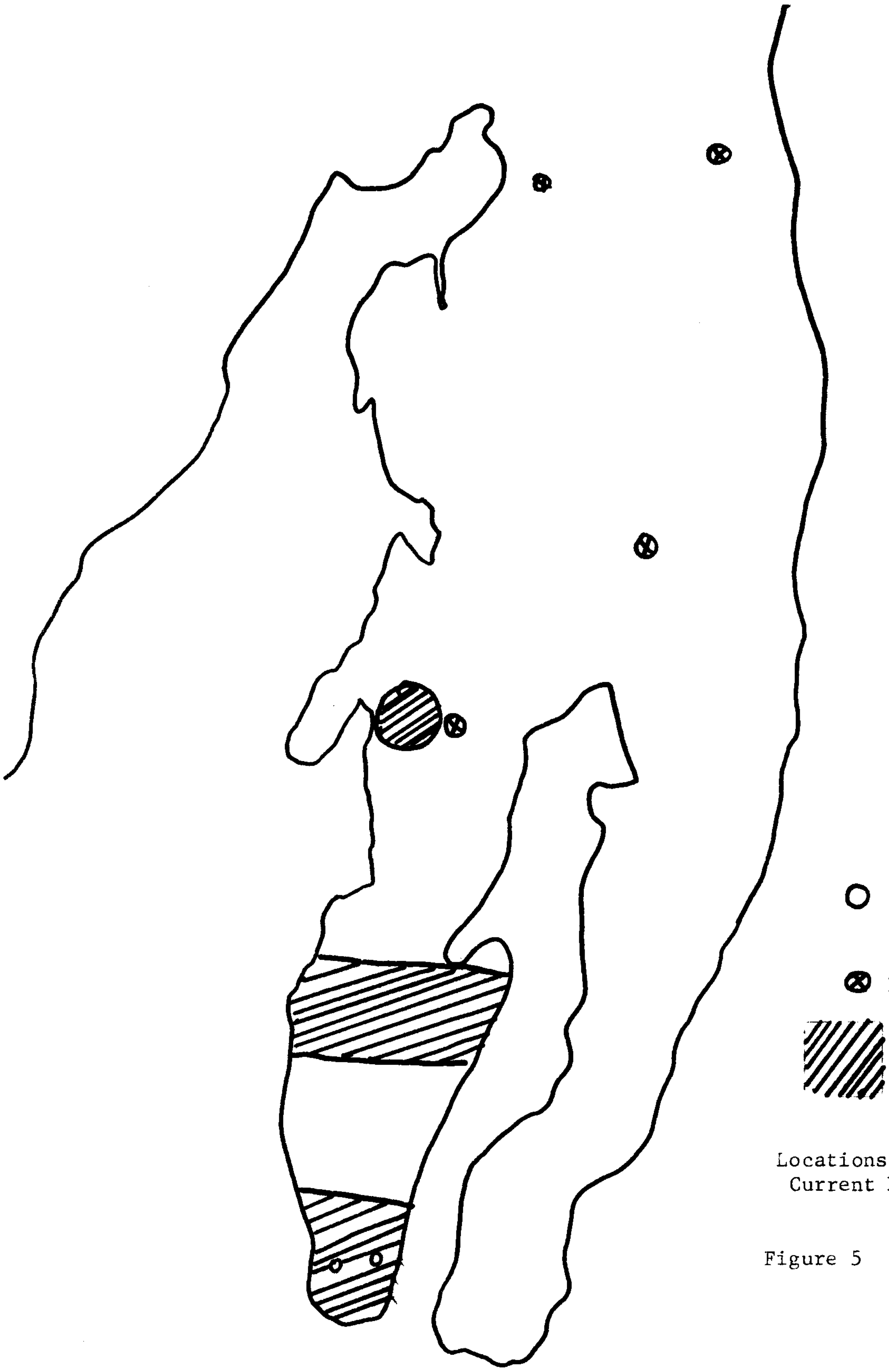
Water Circulation

A mathematical model of the midsummer circulation of the waters of Grand Traverse Bay under action of wind stress is partially completed. Its purpose is to give a picture of circulation laterally at all points in the bay and at two depths, the thermocline and the surface. It will provide a predictive capability relative to estimating transport of water-borne substances among cells or compartments of the bay waters needed in terms (A) and (B) of equation (1) above. From the model one can thus estimate materials' residence times in various portions of the bay which are then used to estimate the rates at which materials are assimilated into the larger body of the Great Lakes waters. Parameters peculiar to Grand Traverse Bay that are represented in the model are dimensions of the basin, bottom friction, and bottom topography. The basic independent variable or forcing input is the wind stress acting upon the water surface. The model also allows for exchange of water with sources outside the bay.

An independent variable of possible interest in the water circulation model (but not presently included) is water draw-off by man. If, for example, a significant percentage of water were diverted from a given volume of water, currents would be artificially created that would draw waters eventually from remote parts of the volume. Changes in the temperature or chemical composition of a lake that might result from such a use would need to be predicted in advance.

A Linear Steady-State Network Model of Materials Balance

A dynamic model of a materials balance consisting of a system of simultaneous equations has three possible modes of behavior as time increases. There may be unlimited increase or decrease of a variable; there may be attained constant levels of the variables not depending upon time; or there may be periodic solutions. Thus when the derivatives of the dependent variables are set equal to zero, the roots of the resulting system of equations identify the combinations of values of the dependent variables within which the steady-state combinations are a subset. By



Locations of Current Measurements

Figure 5

steady-state one means either the case in which the dependent variables attain constant values independent of time or the case in which they yield fixed temporal averages such as would exist whenever the dependent variables never move outside a closed, bounded set. The linear steady-state network model of an open system referred to here can best be visualized in terms of a network flow diagram containing several modes or points of accumulation of "species," i.e., substances of some kind connected by linkages over which material transfer occurs that is governed by physical laws or man-made control rules or both. A basic governing principle in the construction of the model is that <u>necessarily</u> total average input rate to cell i =

$$\frac{Q_i}{D_i} = \frac{\text{volume in cell i}}{\text{residence time in cell i}}$$

$$= \text{total average output rate from cell i} \qquad (2)$$

A set of external sources e_i and sinks d_i identify those inputs and outputs of substances which have the effect of forcing exchanges among cells. The solution is in terms of the ratios $\frac{Q_i}{D_i}$. Knowing the ratios $\frac{Q_i}{D_i}$ and either the residence time D_i or cell volume Q_i the remaining quantity can be determined. It is assumed that in a condition of steady state the sum of all inputs exactly equals the sum of all outputs. The model can be used also for determining <u>feasible</u> sets of external inputs and outputs, which might be interpreted as demands upon a system. For example, the sinks d_i can represent demand points for water over a geographic region where the cells represent aquifers having a fixed carrying capacity. The e_i represent recharge sources to the aquifers and the u_i represent average internal exchange rates of water among cells. A model of this type can also be used to estimate levels of a given substance available for uptake by biological organisms given that the mechanism for transfer of the substance is available.

It is clear that the average throughputs u_i, ..., u_n occurring at the modes or cells must exist if the system has a steady state but that they do not necessarily represent parameters explicit in the formulation of the physical dynamics of the material balance. They can therefore be postulated independently of the dynamic or time dependent model of mass balance but the relationships that they are assumed to satisfy nevertheless must rest upon certain hypotheses or assumptions which are expected to depend upon the type of material being transported and the medium within which it is being transported.

An eight-cell model has been constructed which covers the west arm of Grand Traverse Bay as far north as Old Mission Point and differentiates between waters above and below the thermocline. All major effluents into the west arm are explicitly enumerated as variable inputs along with precipitation, evaporation, and exchange with the upper reach of Grand Traverse Bay.

Model Resolution, Usability, and Long-Range Policy Perspective

The equations of biological production described above constitute high resolution models of the joint behavior of a chemical and biological system. The impacts of physical, chemical, and biological factors upon concentrations of species at various levels within an aquatic ecosystem result in complex interactions which sometimes produce unanticipated or counter-intuitive effects. In order to predict rates of change and accumulations of critical species over time arising from such interacting factors, a level of modelling detail must be incorporated which permits an explicit representation of each factor as it purports to mix with the remainder of the variables in the chain. This variety of possible response or degree of explicitness is what determines the level of resolution of the model rather than the degree to which one variable is sensitive to another variable or a parameter. High resolution models of natural systems typically contain numerous equations exhibiting nonlinearities and require extensive field observational programs to produce data for estimating rates or other model coefficients and for testing tentative relationships that purport to connect causes and effects. A high resolution model of a natural system can be of use to both scientists and managers. It provides the scientist with a predictive tool for anticipating effects upon the system if certain natural conditions or management controls were altered. The effects might be measured in physical units of interest to either scientists or managers. For example, biomass growth in cubic feet or kilograms is understandable to both. What a high resolution model can hopefully provide, that judgment, experience, and professional expertise within a discipline may not provide, is a more or less accurate preview of the effects of several factors interacting within an environment in which feedback mechanisms, both positive and negative, are operative. The fact that high resolution mathematical simulations have the capacity to "anticipate the unanticipated" has been well established in the disciplines of engineering and operations research and the high resolution model has been referred to by Sir Stafford Beers as the answer to the problem of "coping with complexity."

The description given above of the aquatic ecosystem of Grand Traverse Bay by no means represents the highest attainable level of complexity or resolution. One can represent, for example, the nitrogen and phosphorous cycles at high levels of resolution in which concentrations and forms of various compounds of nitrogen and phosphorus are distinguished. Such differentiation permits one to more carefully study the waste absorbing capacity of waters. At the present time only inorganic phosphates and ammonia are represented in the models of biological production which do not permit a study of the impacts of various biological and chemical control mechanisms on the balance maintained within the phosphorous and nitrogen cycles.

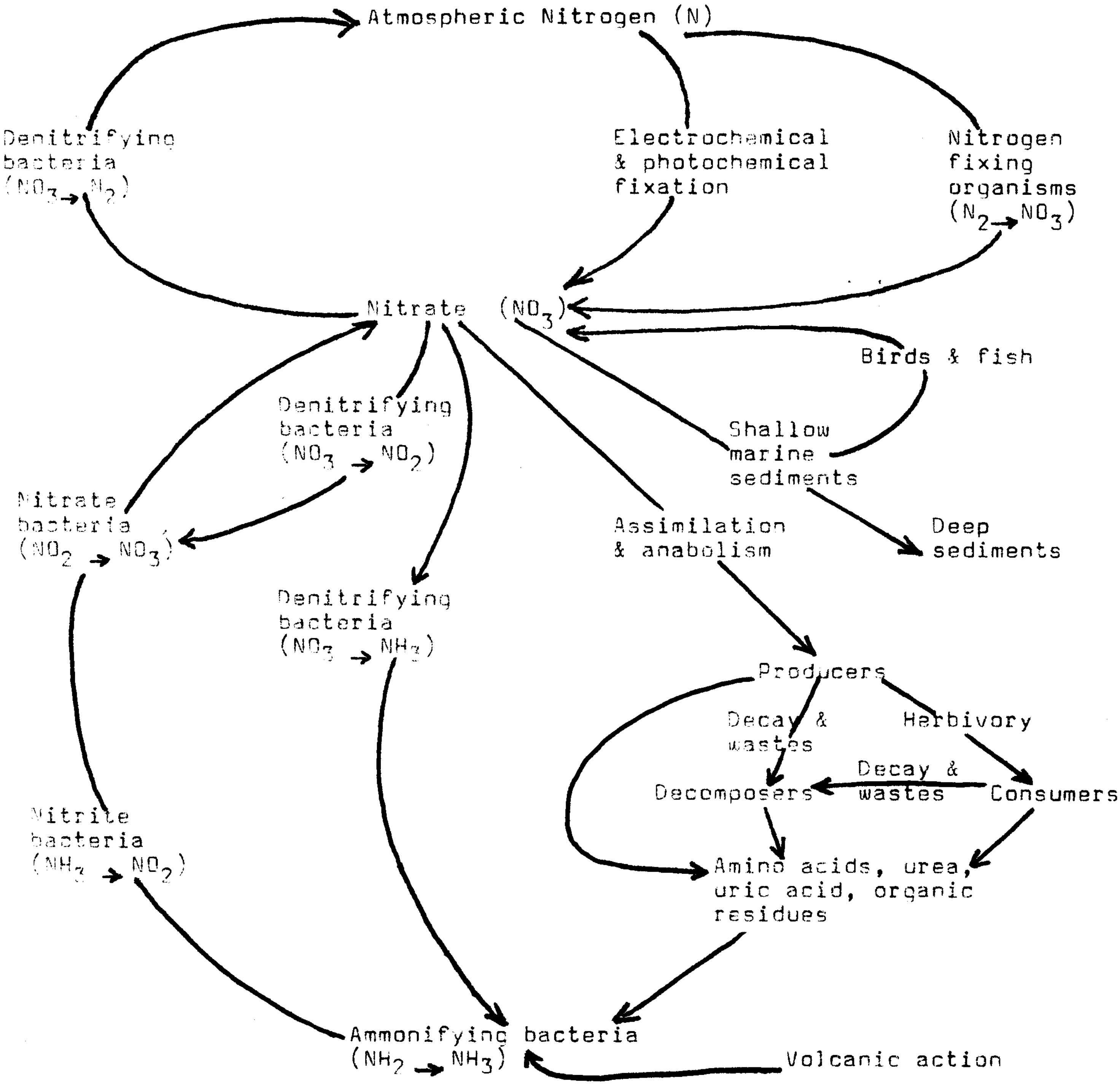
The usability of a high resolution model depends upon its degree of validation, the directness with which the real world management control variables can be related to controllable variables in the model, the controllability of the real world management control variables, the ability of the model to associate clearly undesirable states of the environment with control recommendations, the ability of an individual(s) to communicate in understandable language a set of alternatives obtained from model exercise, and the sensitivity and perceptiveness of those in positions of decision responsibility toward the severity of the problem. Model usability has been proven in engineering and industry particularly in problem situations in which objective criteria are not controversial and can be clearly stated and in which the political factor is not overriding. At the present time all of these factors operate against the usability of mathematical models in management and control of natural resource systems. Moreover, there are difficulties of even perceiving problems of management and conservation of natural resources which have always been present in abundance. The implications of exponential decay in quality and quantity of natural resources are not appreciated until that period of time in which the levels of abundance dip so low as to set counter forces into action that restore equilibrium to the environment but possibly at levels intolerable to man. Not only are biological systems more complex to represent mathematically in a purely technical sense than inanimate physical systems but man's social order--his economics, politics, standard of living, business activity, recreational interests, and energy consumption--are all interrelated to his natural environment which is composed of his earth resources and energy sources from outside the earth. His aspirations and drives along these axes of "activity space" affect his attitude and decisions regarding one's stewardship of natural resources and often conflict with his native sense of resource conservation. Man's mental images or intuitive models of these interrelationships are fuzzy and vague when considered together. It is simply not possible for man to mentally perceive the suddenness with which counter-intuitive or crisis situations may occur or the regulatory forces that nature may bring to bear in order to restore natural conditions to a state of equilibrium. This state may be much different from what man would have chosen had he known the final result at an earlier time. It is a virtual impossibility to assemble a high resolution model incorporating all dimensions of man's activities in regard to his natural resources. Instead, one aggregates parameters and "states of the world" into manageable sets or sectors among which one then constructs relationships either empirically or logically or both. The result is a model of lower resolution giving a macroscopic view of the system it purports to represent. Some economic models are macroscopic. Forrester's world model [3] and urban environmental model [4] are macroscopic in their perception of the systems they purport to reflect. There can be real problems regarding the validity and usability of such models. The intended use of the model affects in an important way the question of validating the model. If the model is high resolution and is to be used as an aid to routine decision making or if it is to be used by a scientist in describing and understanding natural phenomena then it must withstand a comparison with field observations in which it emerges as a credible reflection of the system it purports to represent. If the model variables are defined in aggregate terms thus providing a macroscopic or low resolution view, its use may be to project the impact (in terms of the aggregated variables) of the joint behavior of several sectors of human activity. This is precisely what Forrester's world model purports to do when he considers natural resources, population, capital investment, pollution, and quality of life as the aggregated state variables. Another use of the model beyond the identification of crisis conditions defined in the aggregated terms is to alter management policies in the model in search of ways to improve the performance of the real world system. A third use of the aggregated model is to search for modes of behavior in which the system may be capable of functioning. A fourth use is to identify the counter forces that will tend to return the system to a possibly new state of equilibrium. A simplifying comparison of the high resolution and low resolution models is to think of the latter as giving the broad picture devoid of details in contrast to the former case where more fine-grained details of system behavior are simulated. It seems to be the case that individuals at policy making levels find the low resolution model more useful in gaining insights into the systems with which they must cope since it provides a summarizing picture of events and implications of policies. In this respect it can be a tool for education, training, and testing of policy alternatives. For a low resolution model the validation process utilizes correspondingly grosser measures both at the level of coefficient estimation (for example, the so-called "food ratio" defined and estimated in [3, page 5]) and at the level of the system output or state variable (for example, population level).

Hydrology

A water budget for the entire Grand Traverse Bay drainage basin has been formulated which considers precipitation (P), deep groundwater inflow (Grw), evaporation (E), water storage in the bay (S_1 and S_2) and average inflow rates from gauged and ungauged areas of the watershed (Q_g and Q_u), and average exchange of the bay with Lake Michigan (σ). The explicit statement of the budget is therefore:

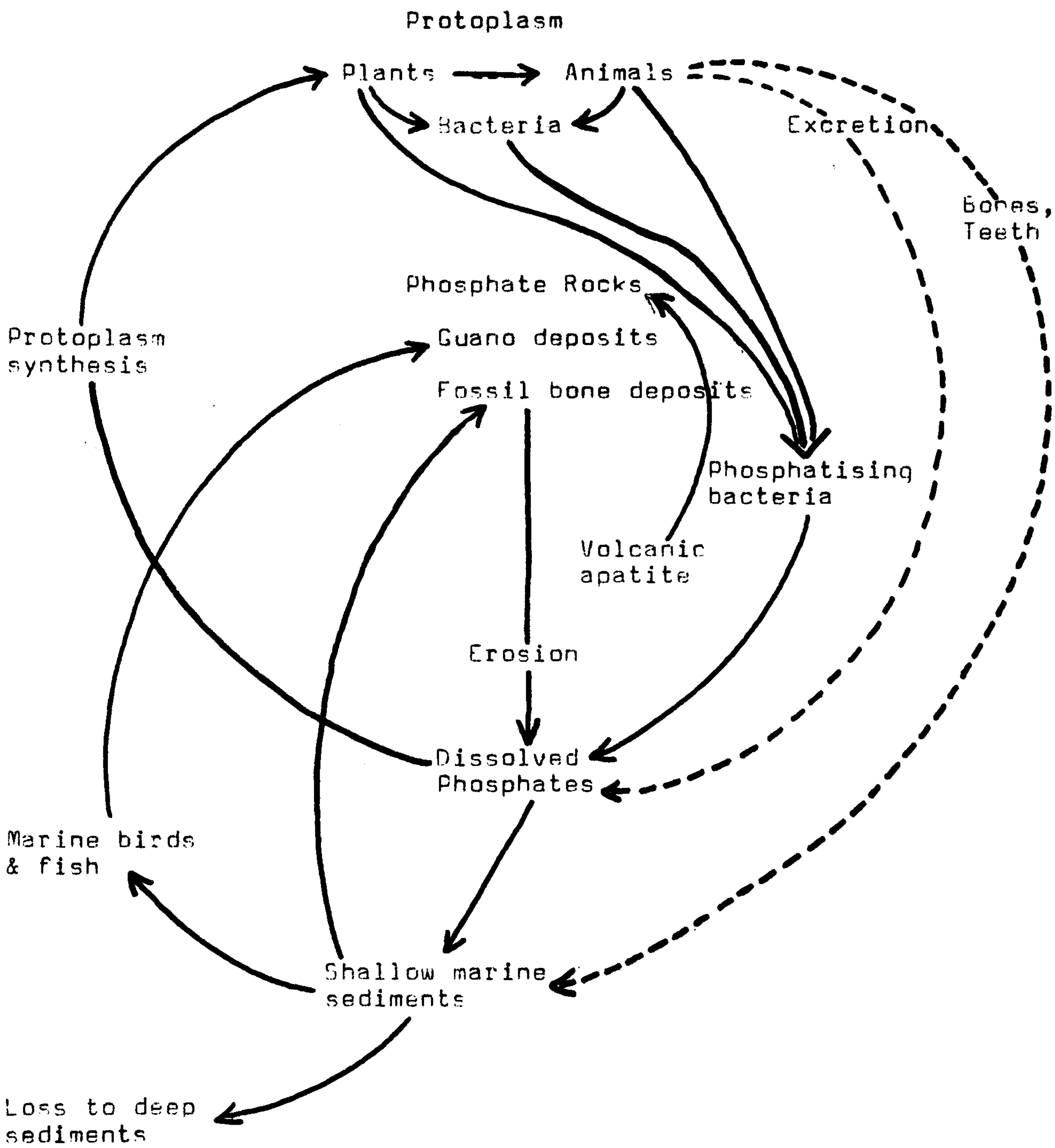
$$[P+S_1+Q_g(\Delta t)+ Q_u(\Delta t)\pm GrW(\Delta t)-E\pm\sigma(\Delta t) = S_2] \quad (3)$$

Equation (3) can be modified to contain terms representing other sources of withdrawal of water from the bay or watershed but would not likely be realistic for the Grand Traverse Bay system. One envisions equation (3) to be one equation in a system described earlier by the steady-state network model covering a larger geographic region from which significant withdrawals of water required for a variety of human uses would be made. As the amount of withdrawals increases a point would be reached after which certain water budgets would be physically infeasible as steady-state conditions. It would be the purpose of the network model to explore the regions of infeasibility. Substantial progress has been made toward developing estimates of the individual terms in equation (3) for the Grand Traverse Bay watershed. The stream-flow rates thus obtained are also used in estimating inputs of chemical pollutants to the bay which are needed in the model of biological production.



THE NITROGEN CYCLE

Figure 6



THE PHOSPHOROUS CYCLE

Figure 7

Little work has been done thus far on developing a network flow model of water availability over a large geographic area such as the Lake Michigan watershed. One can conceive a network of interconnected cells each of which contains a volume of water to which additions and subtractions are made on a continuous or periodic basis. Under a sustained or steady-state condition certain withdrawal schedules from the cells will be physically possible and others will not. Capacity limitations on internal transfer rates among cells are permissable but will require special consideration in the model formulation as they should conform to physical reality as closely as possible. The demands or water withdrawals made upon each cell can be assigned arbitrarily or they can be estimated as the output from a computerized model [5] which generates municipal and industrial water needs in response to levels of municipal and industrial activity specified by the user. (A separate program [6] is available to examine various water conservation practices as they are likely to affect amounts of water that are needed for different uses.) A network flow model describing the availability of water over an area covering the watershed of the Great Lakes would be of value also in studying the Great Lakes as groundwater regulators and for estimating the regional impact upon flora and fauna to the extent that it is limited by groundwater.

Land Utilization

The model descriptions which follow deal generally with questions of land utilization and the impact of patterns of land use upon surrounding aquatic resources. Included are the impacts of agriculture, industry, residential areas, and various other uses and activities that affect availability and quality of water.

Boardman River Water Quality Model

An initial working model has been developed with the following set of input variables into the river system: river flow, agricultural runoff, treatment plant effluents, riverbank housing discharges, campsite discharges, and natural environmental contributions. The natural purification processes of the river and the growth of certain nuisance organisms or plants act on these input variables, thus leading one to observe the variations in certain water quality parameters at different locations of the river. Nitrate, phosphate, and BOD concentrations are some of the quality parameters considered.

Initially, the relationships between various components of the model were described with the help of existing models of physical processes, statistical techniques, field data, and intuition. The model is formulated in an industrial dynamics format, and the DYNAMO language is used to define the relationships. The simulation can be run for any length of time with one week as the time interval between two neighboring observations.

Several preliminary runs were made to examine the various management policy alternatives and their impact on the water quality in the Boardman River. The input variables acting at particular levels were considered to form a policy alternative. For example, building a secondary treatment plant with 90 percent nitrogen and phosphorous removal, accelerated development of tourism, and the control of riverbank housing discharges at certain limits formed a policy alternative in the model. It was observed that promotion of tourism, riverside housing discharges, and campsite discharges have negligible effect on the water quality parameters, whereas the agricultural runoff and treatment plant effluents are the major sources affecting these parameters. In the recent past and the present, it is being observed that the societal objectives are not entirely consistent with purely economic optimal use of resources. The aroused public interest in quality environment, recreation, and aesthetics implies the willingness to share expenses in such a way that it does not necessarily yield the optimal benefit-cost ratio computed exclusively from an economic point of view. One of the uses of the above model could thus be to indicate what intangibles are available at what cost for a whole range of possible alternatives.

The model is presently under modification to incorporate additional detail involving the effects of treated sewage effluent on the Boardman River waters near the mouth of the river. The model has utilized considerable data taken from existing reports describing flow and quality of the Boardman River from Mayfield, Michigan downstream to the river mouth. A detailed report of the model and its use is forthcoming.

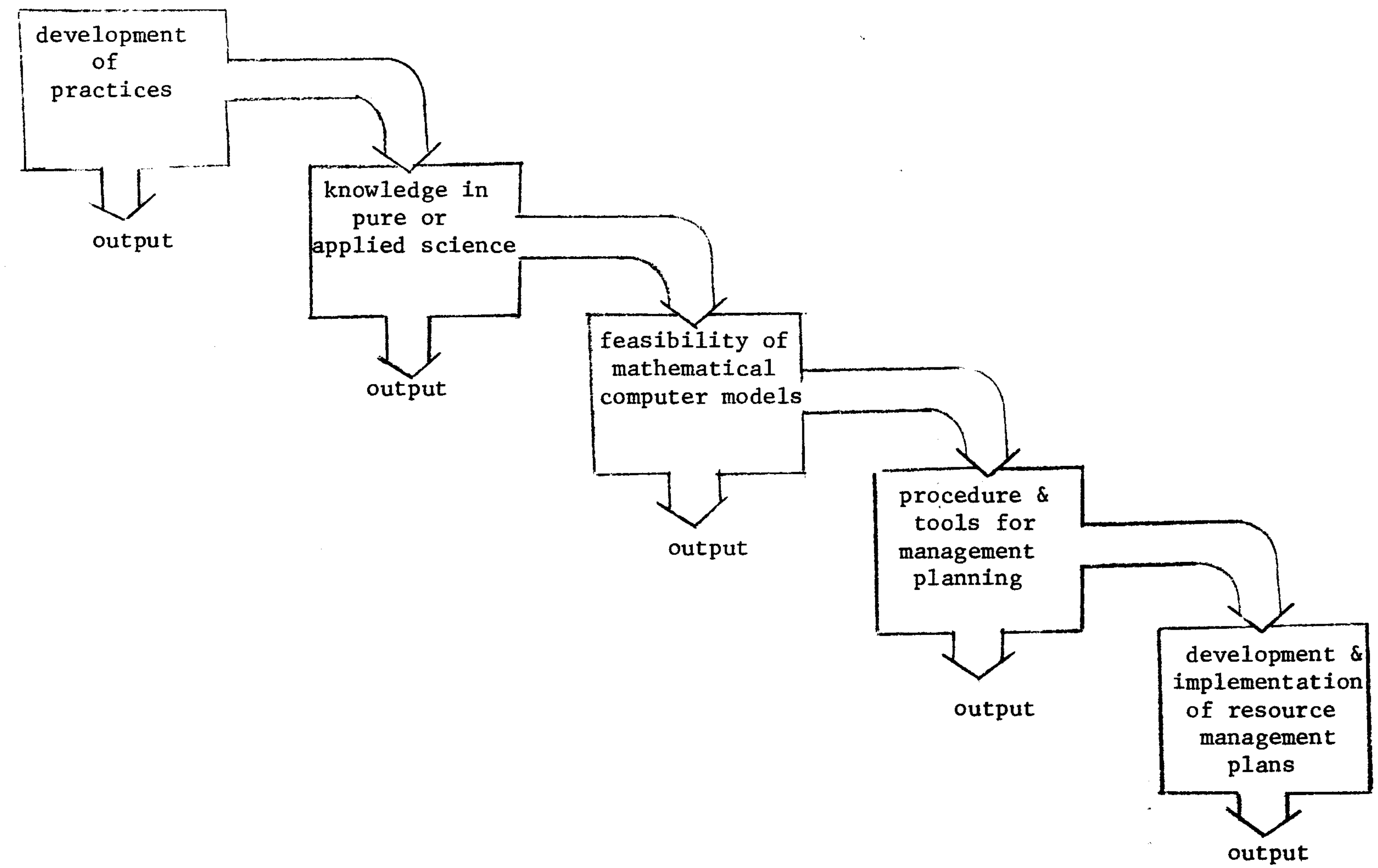
Land Use Optimization Model

The basic structure of the model follows that of the assignment problem of linear optimization theory which is a special linear program. A collection of sites and a collection of potential uses are specified along with a matrix of rating factors which indicate the value (or cost) of each site for each use. In addition requirements may be placed upon the number of sites to be assigned to each use. The assignment of sites to uses which optimizes the total value (or cost) is then determined by a computerized algorithm (Graves-Thrall method) available on the Michigan Terminal System (MTS). It has been suggested that three distinct criteria or "cost" factors be used when solving a land use problem using this method: (a) economic costs or benefits, (b) compatability of a site use with uses of surrounding sites, and (c) political feasibility of an assignment. An exercise is currently underway in which twelve parcels of land owned by the University of Michigan are being evaluated for different uses according to these three criteria. Three sets of assignments will be made and the computer solutions will be compared to actual uses. The exercise should indicate whether the method should be evaluated further.

CONCLUSIONS AND RECOMMENDATIONS

A distinguishing feature of the research program is its scope as defined by study objectives listed under Table A. Emphasis is placed upon each study level as producing: (a) a legitimate end product in itself, and (b) simultaneously contributing an input to a more comprehensive user- or customer-oriented objective (see Figure 8). (It is an instructive exercise to identify a correspondence between individual projects listed by subject area in Figure 1 and study objectives listed in Figure 8.) It has been the usual case that University research groups address themselves to all study objectives shown in Figure 8 with the exception of the development and actual implementation of resource management plans for a specific user. This objective has usually been implemented by means of private contractual agreements between the user and consultants which are often University researchers. In the case where the "management plan" is legislative or executive action by government, the faculty member often provides an input in the form of expert judgments.

The recognition of the urgency and complexity of "environmental management" in the face of population and societal pressures has created increased need and opportunity for University research groups to undertake the task of providing professional support for developing and implementing environmental management plans for the "customer." The customer in this case is an inter-institutional group with at least some vested authority



SOURCES OF PROJECT OUTPUT BY STUDY OBJECTIVE

FIGURE 8

for plan implementation. One example of a University research group in which the overriding objective is to develop and implement an environmental management plan for an inter-institutional authority (with the active working participation of this authority) is the University of British Columbia team under the direction of Goldberg and Holling working with Vancouver officials to develop a Vancouver area plan. The Lake Washington Area Authority is an example of an inter-institutional authority created to solve a water pollution problem but called upon the expertise of individuals on a consultant basis rather than a recognized team of University researchers. Other authorities have called upon research teams to assist in solving pollution problems but these teams have been private rather than University groups. From the preceding discussion and recognition of the scope of expertise (both by discipline and study objective) brought to bear within the Sea Grant Project, one concludes that the option of placing greater emphasis upon development and implementation of environmental management plans for inter-institutional users should be considered. (It is understood that such plans can only be developed with close cooperation of the user agency.) The one example of this type of arrangement presently existing within the sponsorship of Sea Grant is the Shorelands Zoning Project. While it is true that discussions have been held with leaders of Traverse City and surrounding area and a water quality model of Grand Traverse Bay is under development, the concept of a team approach in which University researchers work closely with political leaders and other technical personnel to develop an "area plan," and in which needs, alternatives and goals have been established with local area personnel, has been virtually nonexistent. This is not a criticism but rather a statement of fact and thus provides an option which is now open to the Sea Grant Project, but obviously must receive strong support from the agency with which the University team cooperates. Two possibilities that present themselves in terms of inter-institutional agencies are the "Workable Economic Development Districts" which are delineated by groups of counties and watersheds which cut across political jurisdictions.

From the point of view of developments in terms of field sampling, model-building, and organization achieved thus far within the Sea Grant Project itself, the necessary groundwork seems to have been laid. Whether a heavy emphasis upon the objective of development and implementation of area-oriented environmental management plans would reduce the output at other study-objective levels can only be determined from experience.

From the point of view of development of Sea Grant objectives encompassing Lake Michigan, this concept appears to be workable in that areas bordering Lake Michigan would logically be considered. Moreover, it would provide a logical delineation of an expanse of offshore waters in Lake Michigan with which the research team would be concerned.

An alternative option that is open and seems ripe for pursuance is an increased level of cooperation with the State of Michigan government in the definition, analysis, and development of environmental "management" options on an area basis. The state is then in a position to select (or offer) options for adoption which were arrived at with support of Sea Grant resources. One practical result of the Michael-Ross study might be to identify those individuals or departments in state government with whom communication should be established in anticipation of establishing joint work groups.

LIST OF REFERENCES

[1] Canale, R. P., "A Methodology for Mathematical Modeling of Biological Production," University of Michigan Sea Grant Program Report, 1971, 1536 School of Natural Resources Building, Ann Arbor, Michigan 48104.

[2] Monahan, E. C., "Memo #24 of the Local Meteorology and Water Circulation Research Group of the Sea Grant Program," 1971, 1536 School of Natural Resources Building, Ann Arbor, Michigan 48104.

[3] Forrester, J. W., "World Dynamics," Wright-Allen Press, 1971, Cambridge, Massachusetts.

[4] ________, "Urban Dynamics," The M.I.T. Press, 1969, Cambridge, Massachusetts.

[5] Hittman Associates, Inc., "Main II," Forecasting Municipal Water Requirements, Office of Water Resources Research, U. S. Dept. of the Interior, Contract No. 14-01-0001-1967.

[6] ________________________, "Main C," Computerized Methodology for Evaluation of Municipal Water Conservation Research Programs, Office of Water Resources Research, U. S. Dept. of the Interior, Contract No. 14-01-0001-1991, August 1969.