DREDGED MATERIAL RESEARCH PROGRAM

TECHNICAL REPORT D-76-3

APPLICATION OF ECOSYSTEM MODELING METHODOLOGIES TO DREDGED MATERIAL RESEARCH

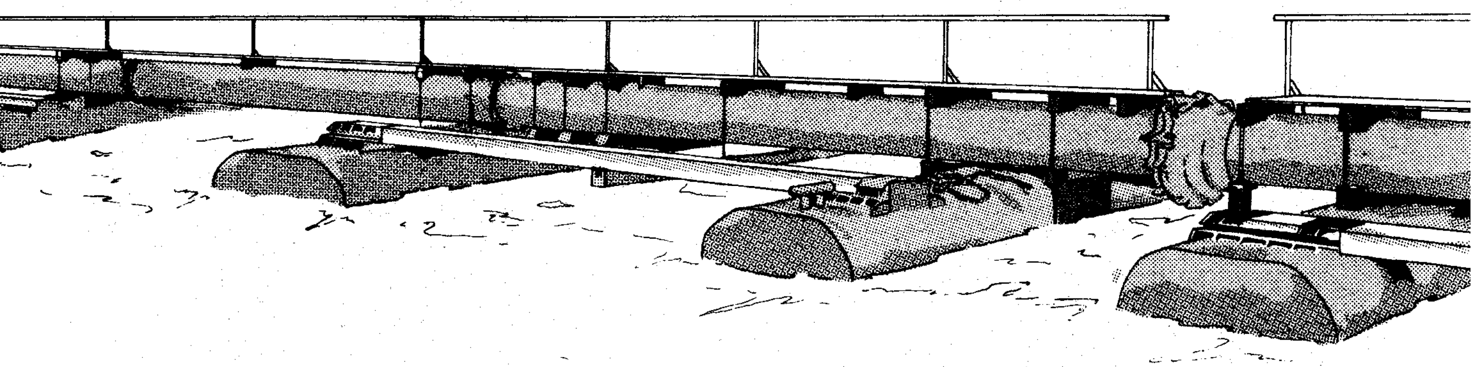
by

Ross W. Hall, Howard E. Westerdahl, Rex L. Eley

Environmental Effects Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

June 1976

Final Report



Prepared for Office, Chief of Engineers, U. S. Army
Washington, D. C. 20314

Under DMRP Work Unit 1D04

DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS
P. O. BOX 631
VICKSBURG, MISSISSIPPI 39180

IN REPLY REFER TO: WESYV

30 June 1976

SUBJECT: Transmittal of Technical Report D-76-3

TO: All Report Recipients

1. The technical report transmitted herewith represents the results of one of several research efforts completed as part of Task 1D (Effects of Dredging and Disposal on Aquatic Organisms) of the Corps of Engineers' Dredged Material Research Program (DMRP). Task 1D is included as part of the Environmental Impacts and Criteria Development Project of the DMRP, which, among other considerations, includes developing techniques for evaluating the effects of dredging and disposal operations on water quality and biological aspects of disposal areas.

2. The research reported herein was accomplished as part of Work Unit 1D04, Application of Ecosystem Modeling Methodologies to Dredged Material Research (Phase I). The primary specific objective was a research planning effort for the DMRP to evaluate the various physical and mathematical environmental modeling techniques that might be applicable to specific DMRP project studies. This investigation was also necessary to conduct a comprehensive review of the current state of the art of ecosystem modeling relevant to the DMRP and applicable to CE District environmental problems associated with dredging and disposal of dredged material. Further objectives were to recommend which types of existing ecological models are applicable to various environmental problems associated with dredging and disposal of dredged material.

3. Three categories of physical models are discussed: bioassays, microcosms, and scaled ecosystem models. Mathematical models can be divided into a number of classes, such as those predicting the effect of allochthonous loadings on the dissolved oxygen budget, determining the partitioning and dynamics of chemical constituents, predicting excessive eutrophication and nuisance algal blooms due to high nutrient loadings, and simulating biological population dynamics and ecological interactions. Physical models are applicable and should be used to understand and quantify the effect of environmental perturbations that cannot be adequately studied under field conditions, to serve as data generators and test systems for the development and evaluation of certain types of mathematical models, and to aid in designing and interpreting results of field studies. Few model applications have been made to specific environmental problems related to dredging and disposal operations. Consequently, the research

for the solution of environmental problems associated with dredged material disposal should include concurrent laboratory, field, and modeling studies.

4. The techniques evaluated in this study are considered applicable primarily to projects where significant environmental impacts are anticipated and a detailed study is required for environmental impact assessment on the evaluation. The choice of specific modeling approach depends upon many factors. Most existing models will require modification, adaptation, and extensive verification before being applied with confidence. It is not feasible to apply ecological modeling and techniques to routine and/or small project evaluations.

JOHN L. CANNON
Colonel, Corps of Engineers
Director

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: Technical Report D-76-3	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): APPLICATION OF ECOSYSTEM MODELING METHODOLOGIES TO DREDGED MATERIAL RESEARCH	5. TYPE OF REPORT & PERIOD COVERED: Final report
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Ross W. Hall Howard E. Westerdahl Rex L. Eley	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: U. S. Army Engineer Waterways Experiment Station Environmental Effects Laboratory P. O. Box 631, Vicksburg, Miss. 39180	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: DMRP Work Unit 1D04
11. CONTROLLING OFFICE NAME AND ADDRESS: Office, Chief of Engineers, U. S. Army Washington, D. C. 20314	12. REPORT DATE: June 1976
	13. NUMBER OF PAGES: 66
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Dredged material
Dredged material disposal
Ecosystems
Mathematical models
Physical models

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report addresses the applicability of physical and mathematical ecosystem modeling methodologies to environmental problems associated with dredging and disposal operations. Three categories of physical models are discussed: bioassays, microcosms, and scaled ecosystem models. Mathematical models can be divided into a number of classes, such as those predicting the effect of allochthonous loadings on the dissolved oxygen budget, determining the partitioning and dynamics of chemical constituents, predicting excessive

(Continued)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (Continued)

eutrophication and nuisance algal blooms due to high nutrient loadings, and simulating biological population dynamics and ecological interactions.

Physical models are applicable and should be used to understand and quantify effects of environmental perturbations that cannot be adequately studied under field conditions, to serve as data generators and test systems for the development and evaluation of certain types of mathematical models, and to aid in designing and interpreting results of field studies. Physical models are most appropriate where processes and interactions within a system are not adequately understood or quantified to be expressed mathematically or where the resulting mathematical relationships are unsolvable with present numerical techniques. Mathematical modeling should be used to provide a means of summarizing and analyzing large amounts of data and complex interactions with many components and to aid in predicting future events. Mathematical modeling can be applied where the assumptions necessary for model development are not excessively limiting.

Few model applications have been made to specific environmental problems related to dredging and disposal operations. Research for the solution of environmental problems associated with dredged material disposal should include concurrent laboratory, field, and modeling studies. Specific modeling approaches are recommended for the following research problem areas associated with dredged material disposal: colonization and ecological succession, biological productivity, material cycling, artificial establishment techniques for habitat creation, direct smothering of benthic organisms, oxygen budget analysis, and pollution criteria development.

The choice of a specific modeling approach depends on many factors. Most existing models will require modification, adaptation, and verification before being applied with confidence. Ecological modeling techniques are not feasible for application to routine and small project evaluations. Large projects with significant environmental perturbations may warrant application of these more extensive evaluation approaches.

PREFACE

This study was supported by the U. S. Army Corps of Engineers Dredged Material Research Program (DMRP), which is administered by the Environmental Effects Laboratory (EEL), U. S. Army Engineer Waterways Experiment Station (WES). The DMRP is sponsored by the Office, Chief of Engineers, U. S. Army (DAEN-CWO-M).

The study was conducted during the period July 1973 to June 1974 under the direct supervision of Dr. R. L. Eley, Chief, Ecosystem Research and Simulation Division, and under the general supervision of Dr. John Harrison, Chief, EEL. Mr. R. W. Hall, Dr. H. E. Westerdahl, and Dr. Eley were principals in the conduct of the study and the preparation of this report. Dr. J. W. Falco made significant contributions to the review section dealing with mathematical chemical models. Ms. K. L. Wong assisted in obtaining and organizing pertinent literature. Dr. K. W. Thornton and Mr. D. L. Robey, Chief, Ecosystem Modeling Branch, and Mr. J. L. Grace, Jr., Chief, Hydraulic Structures Division, assisted in the review and revision of the draft report. Dr. J. W. Keeley and Dr. R. M. Engler were Project Managers for the DMRP.

Director of WES during the preparation and publication of this report was COL G. H. Hilt, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

	Page
PREFACE	2
PART I: INTRODUCTION	4
Background	4
Purpose and Scope	5
PART II: THE ROLE OF MODELING	7
Characteristics of Field Studies and Modeling	7
Advantages of Field Studies and Modeling	8
Considerations in Choice of Approach	9
PART III: PHYSICAL MODELING	11
Bioassays	11
Microcosms	15
Scaled Ecosystem Models	18
PART IV: MATHEMATICAL MODELS	24
D.O. Models	24
Chemical Models	27
Phytoplankton Models	31
Ecological Models	33
PART V: APPLICATION OF ECOSYSTEM MODELING METHODOLOGIES TO DREDGED MATERIAL RESEARCH	38
Ecological Problem Areas	38
Applicability of Physical Modeling	38
Applicability of Mathematical Modeling	39
Application to Colonization and Ecological Succession	40
Application to Species Diversity	42
Application to Biological Productivity	43
Application to Material Cycling	46
Application to Artificial Establishment Techniques for Habitat Creation	48
Application to Direct Smothering of Benthic Organisms	49
Application to Oxygen Budget Analysis	49
Application to Pollution Criteria Development	50
PART VI: SUMMARY	54
Physical Modeling	54
Mathematical Modeling	55
Considerations for Use of Models in Dredged Material Research	56
REFERENCES	58
TABLE 1	

APPLICATION OF ECOSYSTEM MODELING METHODOLOGIES TO DREDGED MATERIAL RESEARCH

PART I: INTRODUCTION

Background

1. Annually, millions of tons of sediment are dredged from the bottom of rivers, lakes, and coastal waters and are discharged into water or onto land surfaces. Much of the concern over the dredging process is related to the possible direct destruction of benthic communities. Less obvious but potentially significant environmental impacts are possible through indirect effects on aquatic and terrestrial communities. Potential indirect effects usually are attributed to physical alterations, such as changes in bottom geometry and substrate, which may result in alterations of current patterns, salinity gradients, and the exchange of biostimulants or toxicants between sediment and water.

2. In the past, most of the concern over disposal operations has been focused on resuspension and subsequent deposition of sediment during open-water disposal. Resuspension of large volumes of sediment may directly or indirectly affect aquatic communities by inhibiting photosynthesis through increased light attenuation, altering aquatic physiochemistry, and releasing biostimulatory or toxic materials. Buildup of sediments through deposition may result in smothering of benthic organisms and changes in habitat diversity.

3. Because of concern over the open-water disposal of contaminated sediment, a trend toward land disposal has developed. Land disposal of dredged material also may have significant environmental impacts and, in many cases, may be more adverse than open-water disposal alternatives. Concerns with land disposal include the possible contamination of groundwater through leaching of contaminated dredged material and the return of toxins and biostimulants by way of several pathways to open waters. Confinement of dredged material may inhibit natural

biological recolonization of the disposal site. Land disposal also may create a concentrated source of hazardous materials which subsequently may enter terrestrial food chains. Land disposal often involves marsh and wetland creation and/or destruction. Disposal operations may affect the value of marshes as breeding and nursery areas and may alter rates of biological productivity. Environmental perturbations in either marshes or estuaries may eventually have significant effects on both systems because of intermixing from tidal action. However, definitive information on functional aspects of these ecosystems is scarce, and many interactions are not understood. Furthermore, energy flows and cycling of nutrients and contaminants between watersheds and marshes, marshes and estuaries, and estuaries and coastal waters have not been adequately documented quantitatively or, in many cases, qualitatively.

4. Within the current state of knowledge, one cannot adequately characterize and predict many environmental problems associated with dredging and disposal operations. In some cases, one cannot even predict whether the overall impact will be adverse, neutral, or beneficial in nature. There exists a need for a more comprehensive understanding of the precise nature of the problems and a capability of predicting their magnitude, areal extent, and duration.

Purpose and Scope

5. Research investigations designed to characterize ecosystem responses and interaction to dredging and disposal operations are required to increase our understanding of environmental impacts and to develop adequate predictive techniques. Two basic research approaches exist: field studies and physical/mathematical modeling (including laboratory simulations). This study was conducted to review available water-quality and ecological-modeling techniques through literature surveys and visitation of ongoing research, and to recommend techniques which are applicable to various environmental problems associated with dredging and the disposal of dredged material. The study was conducted primarily as a research planning effort for the Dredged Material Research

Program (DMRP). However, the information presented should be useful to Corps of Engineers personnel as a general introduction to various physical and mathematical environmental modeling techniques that might be applicable in specific project studies.

PART II: THE ROLE OF MODELING

6. Environmental problems encompass a wide range of chemical, biological, and physical phenomena. Two basic research approaches have been used to investigate environmental problems: field studies and modeling (including laboratory simulations). An identification of the characteristics of these two basic research approaches and a comparison of their capabilities and limitations will assist in formulating research to assess the environmental impact of dredging and disposal operations.

Characteristics of Field Studies and Modeling

Field studies

7. A field study is an empirical approach that may be both descriptive and predictive in purpose. Data are gathered *in situ* usually in the form of inventories of various biological species and water-quality parameters. These data then serve as a basis for inference when comparing or predicting responses of similar systems with those of similar treatments. The assumption is that similar systems will respond similarly to an environmental perturbation. However, in field situations, the existence of unknown or uncontrollable sources of variation often precludes the selection of replicate experimental units that permit precise hypothesis testing or parameter estimation.

Modeling

8. Modeling is primarily predictive in purpose. In modeling, it is assumed that the dynamic behavior of biological, chemical, and physical aspects of ecosystems can be described mechanistically, and thus responses to environmental perturbation can be predicted once rate mechanisms and proper functional relationships are known. A model is defined herein as any physical or mathematical construction developed to simulate or predict dynamic changes which occur in aquatic or terrestrial ecosystems.

9. Three categories of physical models are defined: bioassays,

microcosms, and scaled ecosystem models. Bioassay techniques are used to predict potential short- and long-term responses of a simple biological constituent (tissue, organism, population) of an ecosystem to an environmental perturbation. Microcosm experiments are used to provide unstanding of biological and chemical interactions and to predict environmental responses at the more complex community and ecosystem levels of organization. Both of these study approaches are kinetic in principle and may be used to address the following questions:

- a. How and to what extent is a biological constituent affected by a perturbation?
- b. How fast do these constituents respond to a perturbation?

Scaled ecosystem models are similar to microcosms in ecological complexity, but they provide a capability for establishing physical conditions and spatial gradients that are similar to natural gradients. Thus, these simulations also can be used to study the effect of transport phenomena on ecosystem kinetics.

10. Mathematical models can be divided into a number of classes, depending upon their intended use. Uses include predicting the effect of allocthonous loadings on the dissolved oxygen (D.O.) budget, determining the partitioning and dynamics of chemical constituents, predicting excessive eutrophication and nuisance algal blooms due to high nutrient loadings, and simulating biological population dynamics and ecological interactions.

Advantages of Field Studies and Modeling

Field studies

11. Field studies offer the following advantages over modeling:

- a. An extremely detailed set of data can be obtained that defines the system as it presently exists.
- b. Since data are taken on the natural system, there is less danger of omitting important components or complex interactions of the real system that might occur in formulating a simplistic model.
- c. As opposed to physical models, where the number of

samples is limited by model size, virtually an infinite amount of sample is available for analysis.

Modeling

12. Advantages of using either physical or mathematical modeling approaches to problems include:

a. Environmental parameters operating on a system can be controlled very closely and boundary conditions can be defined so that data are more interpretable and complex interactions can be studied.

b. Experiments can be reproduced any number of times, and a larger number of alternatives can be evaluated within a given time and cost.

c. Proposed treatments can be applied and evaluated in the model without adverse effects to a real ecosystem; i.e., to some degree, an actual test can be run and results predicted before the treatment is applied on a larger scale.

13. Physical models are used in two ways in conjunction with mathematical models. First, they are used to define processes, determine rate coefficients, and describe responses of a given set of biological and chemical constituents to environmental perturbations; and second, they provide a means to calibrate mathematical models to account for effects which are not explicitly included in the mathematical equations. Physical models also may be used independently of mathematical models when systems are too complex to be described by a manageable number of coupled equations or when natural processes are not known adequately for mathematical formulation.

Considerations in Choice of Approach

14. As with all alternate approaches, the choice of using models or field studies involves trade-offs in economic as well as technical considerations. In general, physical models require a larger capital investment than field studies while field studies require higher operating expenditures. Both mathematical and physical models simplify the ecosystem under study--for controllability in the case of physical models and for limiting the equations to a manageable number and

complexity in the case of mathematical models. If these simplifications represent an excessive distortion of ecosystem complexity pertinent to the experimental objective, then field studies may be the best research approach. However, if the number of experimental treatment combinations (environmental situations) to be evaluated is large and there is a need to delineate interactions and cause-effect relationships, then modeling techniques, supplemented by prototype calibration and verification, frequently are more appropriate research approaches.

PART III: PHYSICAL MODELING

15. Physical modeling of ecosystem structure and function is not new. However, the potential usefulness of this concept has not been sufficiently examined. Three basic approaches have been used in environmental physical modeling with varying degrees of success and sophistication. Defined broadly, these approaches include bioassays, microcosms, and scaled physical models. Unfortunately, attributes of these various approaches often have been emphasized rather than their inherent assumptions and limitations. In most cases, standard design criteria have not been formulated, critically evaluated, and routinely applied. As a result, there have been few successful attempts in applying these research approaches for the solution of environmental problems. A review of the three physical modeling approaches will be presented with the following objectives:

a. To state the classical definition or use of each research approach.

b. To describe briefly any transitions the approaches have undergone and to discuss current research applications.

c. To identify the major limitations and advantages of each approach.

Bioassays

Basic approach and uses

16. Bioassays were developed originally in the field of pharmacology for determining the strength of a stimulus from the degree of biological response. However, in the environmental field, bioassays have been used primarily to predict the degree of biological response which would be expected to result from a defined stimulus. Specifically, bioassay techniques in environmental studies have included attempts at determining the toxicity and stimulatory effects of various environmental conditions and contaminants. Lawrence and Bacharach[1] stated that "bioassays cannot be legitimately so described unless a standard preparation is used for a comparison of activity with the test

material and as a means of defining the unit in which the activity is to be expressed." Acceptance of this classical interpretation would limit the use of bioassays as toxicity tests for undefined media, including dredged material.

17. Through applications to environmental problems, bioassay techniques have evolved with a much broader range of applications than were originally intended. Bioassays are now used extensively to establish criteria for critical levels or concentrations* of an environmental variable based on the response of a sensitive biological test material.** The test material usually represents tissue, organism, or population (species) levels of biological organization.

18. Inherent with classical bioassay techniques as applied to environmental studies are the requirements of:

- a. A controlled physical environment (e.g. temperature, turbulence, volume, lighting) which usually is constant for a single test but may be varied in different tests.
- b. An appropriate test material (e.g. the most sensitive life form present in a specific environment, test material with similar genetic history and physiological state, test material amenable to laboratory propagation and handling without significant physiological distortions, etc.).
- c. A knowledge that the state of the test variable is the same as its state in the natural environment.
- d. A capability to reproduce the natural chemical environment in a controlled test environment.

19. Unfortunately, most of the basic requirements have not been adhered to closely and in most cases standard procedures have not been established. As a result, the literature abounds with a confusing variety of bioassay techniques and results. This should not be considered detrimental to the use of bioassay techniques. However, the basic

---

* The phrase "critical level or concentration" is loosely interpreted as that level or concentration of an environmental condition or contaminant which, if exceeded, will result in a significant stimulatory, inhibitory, or possibly lethal response of the test material.

** A "sensitive test material" is considered to be the life form of an organism or population which would be most directly and drastically affected by the test variable.

requirements should be adhered to whenever practicable. When this is impracticable, these limitations must be considered when extrapolating bioassay results to field situations.

20. Typical bioassay procedures used to assess critical concentrations of materials in aquatic environments use chronic and/or acute responses under static and/or continuous-flow conditions. Chronic bioassays involve long-term testing, frequently lasting one or more generations of the test organism. Hence, these tests may require several days to a year or more to complete. Chronic tests are used to detect long-term availability of the test chemical and to determine the cumulative response of the test organism. Generally, chronic bioassay techniques indicate the potential cumulative effects of low chemical concentrations on the test organisms. Acute bioassays, however, involve testing which may last only a few hours to possibly several weeks. The short-term availability of higher chemical concentrations and the immediate effect on the test organism are determined. Continuous-flow techniques are used for either long- or short-term applications where a constant test concentration is desired.[2] Static bioassays are appropriate only to simulate single or pulsed applications of a contaminant and to study the effect of subsequently decreasing concentrations.

21. Research currently is being performed throughout the United States in an attempt to answer questions regarding the applicability of bioassay results for establishment of state and national water-quality criteria and standards. The U. S. Environmental Protection Agency (EPA) has primary responsibility for establishing water-quality standards for freshwater and marine environments. Bioassay research relevant to the development of water-quality standards is being conducted at several major EPA research laboratories including: National Water Quality Laboratory, Duluth, Minnesota; National Marine Water Quality Laboratory, Narragansett, Rhode Island; Gulf Breeze Environmental Research Laboratory, Gulf Breeze, Florida; Pacific Northwest Environmental Research Laboratory, Corvallis and Newport, Oregon; and Southeast Environmental Research Laboratory, Athens, Georgia. In addition to the major bioassay research efforts being conducted by these laboratories, pertinent

bioassay research is also being conducted by other EPA research laboratories and field stations, the U. S. Fish and Wildlife Service, National Marine Fisheries Service, Department of the Navy, various universities and consulting firms, and the Corps of Engineers at the U. S. Army Engineer Waterways Experiment Station (WES). These research efforts are using both static and continuous-flow bioassays to evaluate the eutrophication resulting from excessive nutrient loadings and the toxicity of water-quality contaminants such as pesticides and heavy metals to a variety of biota including bacteria, algae, protozoans, pelagic and benthic invertebrates, and fish. A detailed survey of available bioassay techniques and institutional capabilities is being conducted for WES by Wapora, Inc. (DMRP Task 1D02). It is recommended that Corps field offices anticipating the need to apply bioassay techniques in specific project studies should contact WES for more detailed information and specific guidance on appropriate techniques and institutional capabilities.

Limitations and advantages

22. Several limitations to bioassay tests should be recognized prior to application to field problems, including the basic assumptions stated previously. Lee has reviewed pertinent chemical reactions which must be considered in any bioassay test as possibly influencing the results of the test.[3] Included as potentially important factors are various oxidation-reduction reactions, precipitation, gas transfer, sorption, biochemical transformations, complexation, ionic balance, hardness, pH, and solubility.

23. A problem often overlooked by investigators is the possibility of misinterpreting bioassay results because of the analytical method used for measuring concentrations of the contaminant being tested. Many analytical methods are not specific for the particular form of the element or compound causing the observed bioassay response. It also is important that chemical reagents used in bioassays are pure enough so that obvious test effects are not masked or altered by contamination. Because of these and other similar problems, Burdick concluded that results of bioassays are specific for a particular water

and set of assay conditions.[2] He suggested that toxicity values from bioassays should never be applied as water-quality standards other than for the specific water investigated.

24. In summary, bioassay tests, as used in environmental research, indicate potential effects of test variables on selected biota under a specified set of environmental conditions. Bioassay methods are not refined sufficiently at this time for their results to be used as the sole basis for specifying standard "critical concentrations" applicable to different environments; however, they are useful tools when used in conjunction with other research approaches for formulating and evaluating criteria for specific materials in specific environments.

Microcosms

Basic approach and uses

25. A traditional objective of ecological research has been to understand how physical, chemical, and biological factors interact to control complex systems whose functions involve one-way flows of energy, recycling of matter, and a degree of homeostatic maintenance. More recently, environmental legislation has established requirements for detailed evaluations of the net effects of man's activities on ecological systems. The physical size and associated logistical problems of natural ecosystems; the many physical, chemical, and biological variables and their interactions; and the lack of adequate field equipment and methodologies have traditionally limited field studies of ecosystem processes. Hence, the need was recognized for the development of micro-ecosystem simulations (microcosms) where selected environmental variables could be controlled and boundary conditions could be defined. The microcosm approach has been shown to be partially successful for studying the effects of environmental perturbations on the metabolism, mineral cycling, and population dynamics of complex biological communities. The microcosm approach in essence is a bioassay technique for community and ecosystem levels of biological organization.

26. Beyers has suggested that a "functional ecological unit

isolated from the rest of the world" comprises a microcosm.[4] The procedure usually involves removing a sample of discernable biotic and abiotic components of interest from a prototype ecosystem and placing these components in a suitable experimental container. However, defined axenic cultures also have been used.[5] The microcosm is routinely studied under specified conditions, e.g. light intensity, photoperiod, temperature, and circulation rate (if appropriate), in an attempt to mimic the field prototype.

27. The classical approach involved an initial establishment followed by a period for development of steady-state conditions with respect to biotic and abiotic components in the microcosm. When community metabolism or growth rates stabilized, the microcosm was perturbed and observations were made. The classical assumption was that the ecosystem under study was in a quasi-steady state on a short-term basis; hence, the microcosms were allowed to approach a steady state prior to making comparisons with the prototype. Ecological process rates do vary seasonally and as a function of state of ecological succession, and these factors must be considered in microcosm studies. However, the basic mechanisms of ecological processes are independent of steady-state considerations, and microcosm techniques can be used to study these processes during ecological succession. To study successional patterns, sterilized or defined media are inoculated with a natural seed of biological material and community development is followed. Various experimental treatments may be established to evaluate effects of different environmental conditions and perturbations. Traditionally, the microcosm approach has not included mass, momentum, and energy transfer as design considerations. Hence, investigations primarily are limited to evaluation of the effects of environmental perturbations and diffusional transport.

28. Microcosms have been applied in ecological studies of estuaries,[6-12] streams,[13-18] and lakes.[19-24] Microcosm approaches have been applied less frequently to terrestrial systems, but the concepts are equally valid. Odum and Hoskin demonstrated that the ratio between productivity and respiration, the range of chlorophyll

concentrations, assimilation efficiencies, and species diversity in stream microcosms were similar to those of natural communities.[25] McConnell used microcosms to qualitatively investigate the relationship between fish production and primary productivity.[26] McIntire and Phinney showed that values for gross primary productivity in microcosms were within ranges similar to those measured in natural systems.[16]

Advantages and limitations

29. An obvious advantage of the microcosm approach over field studies is that it enables rigid control of arbitrary ecosystem boundaries. Because of their relatively small size, it is argued that microcosms can be replicated for statistical comparison and manipulated in controlled experiments at the ecosystem level of study.[27-30]

30. The physical size of microcosms has ranged from small flasks[4] to outdoor systems consisting of large concrete tanks[10] and ponds.[11] Arguments for the use of larger systems are that macroscopic ecological processes can be studied by inclusion of a greater variety and larger organisms, larger genetic reservoirs (and thus a greater range of environmental tolerances), larger geochemical reservoirs (thus lessening the chance of depletion of essential nutrients), more realistic physical conditions such as atmospheric reaerations, and a greater amount of material for repetitive sampling. Advantages for using smaller microcosms include the ability to evaluate a larger number of environmental conditions or perturbations, ease of handling, and the statistical advantages of independent observations on true replicate experimental units and freedom from sampling perturbations when an entire experimental unit is sacrificed for analysis.

31. Ecosystem processes influenced by spatial gradients and transport phenomena have not been adequately considered in traditional microcosm studies. Without consideration of these influences, results of microcosm studies can only provide an indication of potential biological community responses to selected types of environmental perturbations, and caution must be exercised in their application to field situations where spatial gradients and transport phenomena are important.

Scaled Ecosystem Models

Basic approaches and uses

32. To differentiate traditional microcosm techniques from more realistic physical simulations of ecological systems in which geomorphometry, transport mechanism, and spatial gradients are considered, the term "scaled ecosystem model" has been coined. The study of ecosystem kinetics in scaled physical simulations is a relatively new and unproven concept in many respects. However, this approach offers the greatest potential of existing research techniques for significantly advancing the state of the art of ecological research and for evaluating the effects of many types of engineering activities on ecosystem functions.

33. Scaled ecosystem models (SEM's) are forced mechanically to create similar mass, momentum, and energy transport regimes to those of prototype systems allowing approximately real-time water residence and biochemical rates. SEM's must consider biological and chemical similarities between model and prototype as well as physical and hydrodynamic similarities. As a result, the momentum equation is not an appropriate design parameter, and geometric scaling is not as critical in the design of SEM's as in physical hydraulic models. Considerations of mass transport (e.g. advection, dispersion, and reaeration) are included as design criteria for model scaling since spatial and temporal variations in biochemical kinetics can often be attributed to gradients and transport limitations in natural systems. Since the primary objective of SEM is to simulate ecological processes, only those physical and hydrodynamic factors that significantly affect biological and chemical processes need to be simulated; in most cases, these can be mechanically induced. However, certain geometric relationships such as area-to-volume ratios must be kept proportional or distortions must be considered in applying results to prototype systems.

34. Kinetic studies involving biological and chemical transformations to determine the fate of contaminants in stream ecosystems currently are being conducted in a SEM at EPA's Southeast Environmental Research Laboratory, Athens, Georgia.[31] The modeling technique is

based on the ability of the design engineer to properly scale processes rather than physical dimensions. The EPA stream model was scaled on two transport properties, rate of dispersion and rate of reaeration. Hence, the movement of materials through the channel is based on mass-balance expressions. In addition to the SEM research being conducted by the EPA, the SEM approach also is being used as an aid in developing mathematical models of woodland stream ecosystems at Michigan State University under the direction of Dr. Kenneth Cummins. The Environmental Effects Laboratory (EEL) at the WES has used SEM techniques to investigate mineral cycling in marsh-estuarine ecosystems[32] and is conducting research to design SEM's appropriate for addressing environmental problems associated with Corps reservoir-watershed projects.

Comparison of SEM and hydraulic modeling

35. Scaled ecosystem models are similar in some respects to physical hydraulic models, but SEM's include biological and chemical considerations in their design. Both physical hydraulic models and SEM's simulate selected aquatic transport phenomena such as advection, turbulent diffusion, and aeration. In physical hydraulic models, similitude with respect to at least some of these transport mechanisms is achieved by appropriate geometric scaling, adjustment of model surface roughness, and appropriate inflow-outflow regimes. Hydraulic model time is speeded up as model size decreases. In scaled ecosystem modeling, biological and chemical kinetics cannot be predictably speeded up and residence times of water masses in the model and prototype must be approximately equal. Several physical phenomena must be mechanically induced so that mass transport, heat transfers, and biochemical kinetics can remain similar in model and prototype. Since the time factor or scale is a major difference between these two types of physical modeling techniques, a brief discussion of physical hydraulic modeling is included in this report.

36. The use of hydraulic models to reproduce certain natural phenomena primarily is based on the theory of similitude. Complete similitude requires that the systems in question be geometrically,

kinematically, and dynamically similar. The requirement of geometric similitude is impossible to meet when the vertical or horizontal relief of a prototype system must be exaggerated over the other in the model.[33] However, a particular state of fluid motion can be simulated in a model by considering that either gravitational or viscous forces predominate and that a pertinent basis for similitude can be established by equating the ratio of pertinent forces in terms of dimensionless quantities such as the Froude or Reynolds Numbers. Successful modeling requires that the same fundamental character of flow (viscous, turbulent, steady or unsteady) and the one or more predominant force ratios and phenomenon of interest be reproduced or preserved between the physical model and the prototype system. Whereas the objective in applying principles of dimensional analysis is the generalized mathematical representation of experimental data, the objective in applying principles of similitude is the physical representation of a specific set of conditions. Concepts of dimensional analysis traditionally have been used to achieve satisfactory similarity. This method is a mathematical process of generating dimensionless numbers relating model and prototype characteristics. These dimensionless numbers are derived from a set of input parameters which the hydraulic engineer considers important. Verification of hydraulic and other models necessitates the comparison of dimensionless relationships generated from field and model data.

37. Birkhoff suggested an alternative method for achieving similarity known as inspectional analysis.[34] This technique is based on physical laws which describe flow processes. Usually these laws are stated in the form of differential equations related to mass, momentum, and energy transfer. Once the equations are identified, they are rewritten in dimensionless form. This results in the expression of dimensionless groups of physical quantities appearing as coefficients in differential equations. The prototype and model will have identical fluid processes if the dimensionless equations describing both systems are identical; this will only apply when the model and prototype are geometrically similar. Verification is achieved when the coefficients

for both model and prototype in the dimensionless differential equations are equivalent.

38. The first step in designing a model is the selection of a scale such that similarity of the predominant force ratio or phenomenon being studied and the fundamental character of flow is preserved in the model. Customary practice is to start with geometric similarity, unless there is some definite purpose to be served by distortion. Models are distorted when a departure from geometric similarity serves some definite objective and the results are limited to this objective. Distortion is usually required in models of reservoirs, rivers, floodways, harbors, and estuaries for which the horizontal dimensions are large in proportion to the vertical ones. In such cases, the horizontal scales are limited by space and cost restrictions. When these scales result in model depths and slopes that are too small to yield significant results, a vertical exaggeration or a distorted vertical scale is required. Many valuable studies have been made with distorted models. In movable-bed models, the distortion should be kept as low as possible without reducing bed movement too much. Economy considerations dictate that the model be as small as possible and still yield valid results. There is a minimum size for each type of model. Current practice is to follow precedent, when available, and to size the model as large as is permissible with available facilities (space and water supply in particular). When the state of flow is unsteady, the additional factor of acceleration head is introduced. Since all parameters change with time when the flow is unsteady, the equation of motion takes the form of partial differential equations, which can be solved only by approximate methods. Under such conditions a model can be regarded as an integrating machine. In general, a model that is valid for steady flow at different stages is equally valid for unsteady flow. It is to be noted that distortion of the linear scale does not alter the suitability of a model to reproduce transient conditions if the resistance is adjusted accordingly. When the principal factor is tidal flow, it is usually necessary to use a distorted or vertically exaggerated model to obtain a measurable tidal range in the model. The larger depth may also be required to give

velocities high enough to move bed material. In problems involving waves, the particular type of wave controls the allowable distortion.

39. Hydrodynamics and physical water-quality characteristics (temperature, salinity, etc.) have been successfully studied using physical hydraulic models. However, nonconservative processes have not been addressed in conventional physical hydraulic models because certain chemical and biological reaction rates will not conform proportionally with the model time resulting from geometric scaling.

40. No matter how carefully a model is designed and constructed, it does not contribute an automatic solution but provides data and infomation that require intelligent interpretation based upon the experimenter's knowledge of basic mechanics and hydraulics as well as upon his experience. A model is designed and operated according to a similitude law that is seldom completely satisfied, and the resulting limitations must be respected in the prediction of prototype behavior. Interpretation of model results in terms of the prototype, within the limitations of the type of similitude prevailing, is the most critical phase of the model study. As with all simulation techniques, some field studies of prototype systems must be conducted to obtain appropriate data for calibration and verification purposes.

41. SEM offers a greater diversity of potential applications to environmental problems than other physical modeling approaches. SEM attempts to simulate, through appropriate model design and operation, physical aspects of prototype systems that are important to ecological processes. The complexity of ecosystem processes which theoretically can be investigated approximates many field-related phenomena.

42. With the use of computer-controlled in situ monitoring and automated sampling and chemical analysis, the frequency and accuracy of data collection in models are much greater than is possible to achieve in the field. Hence, kinetic data necessary to estimate various process rates are much easier to obtain. In comparison with field studies, the initial capital investment for appropriate simulation facilities is high but the cost per sample and manpower requirements for operation are lower, and the variety of feasible experiments and

interpretability of results are greater. However, as the size, complexity and realism of the SEM are increased, the statistical advantages of using several replicate experimental units usually must be sacrificed for practicable reasons of cost and time. Thus, SEM offers a compromise between the complexity and realism of field ecosystems and the experimental advantages of simpler microcosms or bioassays.

43. As with microcosms, the usefulness of SEM is restricted to those ecological processes dominated by relatively immobile or small organisms whose functions are not significantly influenced by spatial boundaries. Functions of mobile organisms such as vertebrates can be simulated indirectly by various means, but, in general, SEM is not suitable for studying directly higher elements of biological food chains. However, ecosystem functions such as mineral cycling and energy flow are dominated by microorganisms and relatively immobile or sessile organisms, e.g. rooted plants. SEM offers significant potential for understanding and quantifying environmental impacts of engineering activities on these functions.

44. Properly designed and operated SEM's may have considerable value as research tools for: (a) developing and verifying mathematical ecosystem models, (b) predicting environmental impacts of perturbations on a total ecosystem and on interactions between ecosystems, (c) understanding basic interrelationships between biological and physical processes, (d) interpreting field studies, and (e) focusing field studies on relevant processes.

PART IV: MATHEMATICAL MODELS

45. For convenience of discussion, four rather arbitrary and indistinct classes of mathematical water-quality and ecological models are identified: (a) D.O. models, (b) chemical models, (c) phytoplankton models, and (d) ecological models. Models are divided into these classes according to their emphasis and resolution of various water-quality and ecological phenomena. D.O. models emphasize the simulation of temporal and/or spatial variations of D.O., frequently using approaches with a minimum of biological and chemical complexity. Chemical models emphasize the reactions occurring among various chemical species in natural waters. Phytoplankton models address the problems of excessive microscopic plant growth of often undesirable species. Eutrophication is usually assumed to result from an increased discharge of nutrients into a water body. The emphasis is on simulating phytoplankton population dynamics and the environmental factors directly affecting phytoplankton. Ecological models are characterized by their inclusion of numerous biological species or species aggregates as well as food chain and species interactions. Models which address ecological succession are included in this class. A fifth class of models, fishery yield models, was reviewed during this study, but it was concluded that they are not sufficiently applicable to problems associated with dredged material disposal to be included in this report.

46. For a given class of mathematical models, formulations have been developed for lakes, rivers, and estuaries. However, the most significant difference between models developed for these diverse environments is in the description of hydraulic transport phenomena. Functionally, the ecology of these environments is similar in many respects. Their mathematical descriptions differ mainly in the selection of pertinent components and the structural relations between components.

D.O. Models

47. The temporal and/or spatial variation of D.O. in streams

has been modeled extensively. Streeter and Phelps originally assumed the D.O. concentration in a stream was influenced by two independent reactions: bacterial respiration as indexed by the biochemical oxygen demand (BOD) and surface reaeration.[35] Later modeling emphasis has been on extending and refining the Streeter-Phelps formulation by using a more generalized mass-balance approach and by the inclusion of additional processes such as benthic oxygen demand, scour and deposition of benthic deposits, photosynthesis and respiration of aquatic plants, and nitrification. Additional work is needed to adequately model some of these processes.[34] Stochastic modeling techniques are being developed for generating the probability distribution of D.O. concentrations in both streams and estuaries.[36]

48. D.O. models that have been developed sufficiently to be generally applicable to streams include DOSAG-I,[37] QUAL-I,[38] EPA Columbia River Model,[39,40] and the Hydro-Quality Simulation Model.[41] D.O. models generally contain algorithms for calculating temperature, D.O., BOD decay, and, in some instances, concentrations of conservative substances. These models assume steady-state flows and have not been adequately evaluated for unsteady flow conditions such as those occurring below impoundments with hydroelectric power-peaking operations. Water Resources Engineers, Inc., under contract with the EPA, has modified the QUAL and DOSAG model systems, resulting in the versions QUAL II and DOSAG III. In addition to previously stated components, these versions also contain algorithms for calculating the concentrations of various nitrogen forms, phosphorus, chlorophyll A, and coliforms. The primary difference between QUAL II and DOSAG III is the integration routine. QUAL II uses a finite difference scheme to solve the continuity equations, while DOSAG III uses an analytical integration routine. The same data set produces nearly identical results for the two models.

49. D.O. models developed for estuaries include those proposed by Feigner and Harris,[42] Leendertse and Gritton,[43] and Shindala et al.[44] The extension of stream D.O. models to vertically mixed estuaries and lakes is rather straightforward, assuming that hydrodynamic transport phenomena are reasonably characterized. However, in many estuaries and

lakes, thermal or chemical stratification produces considerable variation in the vertical distribution of D.O.

50. The earliest attempts at modeling D.O. in stratified systems were to apply methods developed for streams only to the mixed surface or euphotic zone. Bella first proposed a one-dimensional mechanistic model of D.O. in stratified impoundments.[45] Using the model in a very simplified form, assuming insignificant vertical advective flows, and with little data on oxygen sources and sinks, Bella did demonstrate the significance of respiration and vertical dispersion on D.O. concentrations in the lower hypolimnetic zone of impoundments. Markofsky and Harleman, using a one-dimensional thermal model to generate the density gradient, simulated D.O. variation in stratified impoundments as a function of BOD.[46] The assumptions were made that the surface waters were D.O. saturated to an arbitrary depth (generally the top metre of the thermocline) and that no transfer of oxygen occurred across the sediment-water interface. Carroll and Fruh simulated D.O. in the hypolimnion of an impoundment by extending Bella's formulation to include bottom-sediment oxygen demand and microbial respiration (indexed as a first-order BOD decay), both exerted uniformly over the hypolimnetic water column.[47] The WESTEX model, which was developed at the WES, incorporates similar mechanisms for D.O. simulation but provides improved techniques for considering selective withdrawal and reservoir hydrodynamics.

51. A number of D.O. models are discussed as phytoplankton and ecological models. This demonstrates the arbitrariness of the categorization of water-quality and ecological models as generality and comprehensiveness are achieved through consideration of additional ecological components and interactions.

52. In summarizing the review of D.O. models, the following conclusions are drawn.

- a. For those classes of problems for which one wishes to investigate the assimilative capacity of streams and vertically mixed estuaries and lakes to heavy, point-source, organic waste enrichment, experience and general agreement between model simulation and prototype behavior suggest that the more significant processes have been identified.

b. However, for pristine or mildly perturbed systems in which processes such as photosynthesis, algal respiration, and decomposition play dominant roles, the understanding and characterization of significant processes are less well known and the utility of models shifts from one of prediction to data reduction and summarization. Adequate model evaluation of the D.O. budget in these cases requires experience and interdisciplinary expertise.

Chemical Models

53. All bodies of water contain chemically active materials which affect the biological components of the system either by stimulating or inhibiting biological activity. In addition, materials such as mercury, other heavy metals, and pesticides can be transported up the food chain from microorganisms to fish and thereby cause a potential health hazard to consumers. It is difficult to distinguish processes governed solely by chemical kinetics from those that are biologically mediated since chemical and biological processes are closely coupled. Obviously, when attempts are made to simulate the dynamics of biologically active chemical species in ecosystems with models based primarily on chemical equilibrium,[48] model results frequently do not agree with field observations.[49] Examples of chemical equilibrium models, including the modeling of adsorption of solutes on solids, are those of Falls and Varga;[50] Morel, McDuff, and Morgan;[51] and McDuff and Morel.[52]

54. In modeling chemical reactions occurring in aquatic ecosystems, it is useful to make certain assumptions that are closely approximated in real systems. For very fast reactions, it is usually assumed that these processes are instantaneous. For well mixed bodies of water, these fast reactions may be assumed to be at equilibrium. In a distributed system, a global equilibrium may be assumed throughout the water body for those sets of materials which enter fast chemical reactions exclusively.

55. The assumption of global equilibrium might be termed a zero-order approximation to water chemistry reactions. It is a severe assumption that is valid for few aquatic ecosystems. A first-order

approximation to chemical kinetics is the assumption of local equilibrium. Models employing this approximation may represent systems in which the transport of reactants and products into a defined element of fluid is slow compared with the rate of chemical reaction. Essentially, it is assumed that the reactions in a given element of water are at equilibrium at a given time in these models. As material is transported into the element, the equilibrium shifts to partition the added or decreased amount of given constituent to the various forms involved in chemical reactions in proportion to the equilibrium partitioning.

56. Equilibrium relationships for carbon, phosphorus, nitrogen, and other compounds can be included in the same set of equations. In principle, any number of reactants can be considered. Solubilities of both gases and dissolved solids can be included, but eventually a practical limitation of computer memory size and execution time is reached.

57. For slower reactions occurring in either well mixed or distributed water bodies, the actual rates of reactions must be evaluated. If variations in concentrations of materials with time or distance are small, these reactions can be approximated as pseudo-first order. For a set of coupled chemical constituents, the rates of reactions of all species can be represented by the following equation:

$$(R) = [K](C) \tag{1}$$

where

(R) = n-dimensional column vector containing the rates of reaction of each chemically distinct species

[K] = n by n matrix of pseudo-first order rate coefficients

(C) = n-dimensional column vector of species concentrations

58. When substantial changes in the concentration of various chemical constituents occur, first-order kinetic models have limited value. Most chemical reactions in fact are not first order, and thus the rates of reactions involving most compounds are not linear functions of reactant concentrations. In such cases, rate equations involving the proposed mechanism of reactions must be incorporated into the model.

Inclusion of these complex kinetics generally leads to a set of nonlinear equations which must be solved by numerical techniques to predict the temporal and spatial distribution of the reactants in an aquatic ecosystem.

59. In equilibrium and local equilibrium models, equilibrium constants are required for each reaction considered. Although there is a large volume of data on various chemical reactions, most data are for specific temperatures and final water solution composition. Consequently, some method of predicting effects of various constituents and temperatures on equilibrium coefficients is required. Classical thermodynamics provides the means to predict these effects.[53] A good example of the required type of thermodynamic data is presented by Kramer.[54] A method for computing equilibria in aqueous chemical systems has been described by Morel and Morgan.[55]

60. Shifts in equilibrium due to changes in concentrations also can be estimated. Such changes usually involve the precipitation or volatilization of excess materials from the liquid phase. In case of precipitation, processes are extremely rapid and at least local equilibrium can be assumed. Stumm and Morgan present a brief description of these phenomena.[56] An example which includes this aspect of chemical modeling is Kramer's application of a calcite model to the Great Lakes.[57]

61. In the case of dissolution of materials from gases or solids, processes are relatively slow and often the assumption of local equilibrium is too inaccurate. In such cases, a model that describes the rate of dissolution must be used. Most models that include these rate processes assume a diffusion limiting step. In the case of gas dissolution, a diffusion resistance is postulated at the air-water interface or at the gas bubble-water interface for submerged gas pockets. For solid dissolution, a diffusion-limited boundary layer around the dissolving material usually is assumed. Since these processes are diffusion limited, the diffusivity of reacting materials must be known in addition to equilibrium constants. Unfortunately, there are not nearly as many data on diffusion coefficients as there are for equilibrium coefficients. Furthermore, the diffusivities of materials in water are strongly

dependent on temperature and solution composition. Theories to account for these dependencies are not adequate at this time;[58] consequently, more research should be directed toward this area.

62. For slow reactions, the appropriate rate coefficients must be known in order to predict the concentration of reacting constituents as a function of time and position. Here again, less is known in comparison with equilibrium coefficients. Often mechanisms of reactions are not fully understood and, consequently, constant coefficients are functions of the solution composition. Temperature dependencies of rate coefficients tend to be exponential but are valid only over relatively narrow fluctuations.

63. In summarizing the state of the art of chemical models, the following conclusions are drawn.

- a. Equilibrium models for dissolved compounds are on a solid theoretical basis. Large amounts of equilibrium data exist for chemical solutions. More field data are available for marine waters than for freshwater lakes and streams. Significant advances probably will occur with increased application to ecosystem studies. As experience is gained, catalogs of materials and types of environmental conditions under which the equilibrium assumption is valid should evolve. More basic work needs to be directed toward equilibrium partitioning at the sediment-water interface where information on relationships and data bases is not as extensive as in the water column.
- b. The assumption of local equilibrium on a microscopic scale in aquatic systems requires a knowledge of flow patterns and turbulence characteristics to define the model completely. Where molecular diffusion plays a role, the diffusivities of materials of interest must be known as well as effects of temperature and concentration variations. Further research on the measurement of diffusivities of materials must be carried out before these models can be fully used.
- c. Insufficient data on the rates of slow reactions occurring in aquatic ecosystems limit the development of kinetic models. Studies on these rates at realistic concentrations and temperatures must be carried out before these models can be used effectively.
- d. The potential usefulness of chemical models for environmental studies could be increased significantly by

coupling them with biological models. This has not been successfully accomplished and evaluated to date.

Phytoplankton Models

64. Patten has reviewed the earlier phytoplankton production models.[59] The first phytoplankton model to include the major features of phytoplankton kinetics was proposed by Riley.[60] Inputs to the model included temperature, solar radiation, depth of euphotic zone, nutrient concentrations, and zooplankton concentrations. Riley, Stommel, and Bumpus extended the model of Riley to include vertical transport mechanisms of turbulence and cell sinking in order to simulate the steady-state vertical distribution of phytoplankton and nutrients.[61] Furthermore, the phytoplankton, zooplankton, and nutrient equations were coupled, resulting in interdependent solutions. This model represents the first phytoplankton growth formulation in which the interactions of these components are embodied in the model. Steele developed a model based upon the techniques of Riley, Stommel, and Bumpus, and solved for nonsteady-state solutions using a simple two-layer approximation for spatial distribution in depth.[62] Davidson and Clymer, using a model basically similar to that of Riley, Stommel, and Bumpus, explicitly included seasonal variation of temperature and solar radiation in the phytoplankton growth rate.[63]

65. Recently, phytoplankton model development and elaboration have been rapid. Extensions of the models outlined above may be categorized as:

- a. Increases in the number and biological realism of processes, such as nutrient uptake kinetics, influencing phytoplankton dynamics.
- b. Inclusion of multiple nutrients or limiting factors.
- c. Consideration of additional ecological components necessary for the characterization of the cycling of materials.
- d. Incorporation of additional phytoplankton assemblages enabling the simulation of successional phenomena at least on a gross scale.

e. Adaptation of hydrodynamic formulations enabling more precise spatial characterization.

66. Models which have been sufficiently developed to be applicable for simulating some aspects of phytoplankton dynamics in reservoirs and lakes include those proposed by Chen and Orlob,[64] Hydroscience,[65] Baca et al.,[66] and Lombardo.[67] Models applicable to estuarine systems include those proposed by Chen and Orlob[64] and Di Torro et al.;[68] and to rivers include Lombardo[67] and Di Torro et al.[68] Several of these models are also applicable as D.O. models and, in some cases, as ecological models. However, in general, the realism and degree of resolution of the models decrease in higher trophic levels, and model results should be applied only after careful interpretation by interdisciplinary personnel.

67. Numerous models have been formulated to investigate specific details of phytoplankton dynamics. Examples include the effects of cell sinking and convective mixing,[69,70] preferential nutrient assimilation,[71] nutrient uptake kinetics and multiple nutrient growth regulation,[72-74] phytoplankton succession,[71,73-75] and the influence of the stoichiometric composition of algae and bacteria on simulated seasonal variations.[76] More applied formulations address the influence of nutrient diversion on lake recovery,[77] the effects of pulp mill effluent on D.O. through photosynthetic inhibition,[78] and the influence of waste heat addition.[79] Phytoplankton models that presently are sufficiently developed and tested to have some utility for applied problems are either spatially one-dimensional or single-point models. Two-dimensional models have not been adequately developed. The basic hydrodynamic and thermal simulation routines used in the models can have significant effects on the accuracy of phytoplankton simulations. The inability to perform accurate two-dimensional routings of suspended solids and other variables is a major limitation to model usefulness for problem solving. This is also true of existing D.O., chemical, and ecological models as well.

68. General agreement between phytoplankton model simulations and prototype behavior implies that the major environmental relationships are adequately formulated for application and that the models qualify as predictive tools for appropriate applications. With adequate input data

and calibration by qualified users, these models may be used to predict the potential response of functional groupings of phytoplankton to moderate changes in major nutrients and light. However, responses to major perturbations and successional changes in species composition have not been adequately simulated. Field prototype behavior often can be rather precisely simulated by judicious manipulation of coefficients during model calibration. Such agreement between model and prototype does not constitute model verification and provides no assurance that simulations of environmental perturbations will agree with prototype responses. For most types of applications, previous studies have not provided an adequate framework in which ramifications of model assumptions can be systematically evaluated. In some cases, similarly named variables and coefficients represent functionally different entities in different models. Practical applications of existing models should only be made by experienced users familiar with the implications of a specific model's assumptions.

69. In summarizing the review of phytoplankton models, the following conclusions are drawn.

- a. Phytoplankton models have not been verified in most instances. These models are not capable of predicting absolute values under varying environmental conditions.
- b. If all the limitations and assumptions are understood and considered, phytoplankton models may be useful in evaluating minor perturbations to the system such as increased phosphorus loadings or increased turbidity. These perturbations cannot be major or catastrophic, however. Events that significantly alter the species composition of the system presently cannot be evaluated through simulations.
- c. Most of the phytoplankton models are one-dimensional or single-point models. Local disturbances, such as dredging a small bay of an impoundment or estuary, are therefore averaged over the entire system making interpretation difficult.
- d. These models should be applied and interpreted by a multidisciplinary team of qualified individuals.

Ecological Models

70. In contrast to the models previously discussed for which

minimal characterization of an ecosystem for a given problem is frequently an objective, ecological models are more descriptive, emphasizing exhaustiveness and resolution often to the limits of potential data availability. Ecological models generally include numerous biological species or species aggregates and emphasize food chain and species interactions. The prediction of slow or subtle changes in species composition, long-term changes in productivity, food-chain transport of toxic material, and the effects of large perturbations to biological systems requires a greater resolution of the biota and a more accurate quantitative formulation of their interactions than are presently embodied in the existing phytoplankton, chemical, and D.O. models. However, these existing models become indistinguishable from ecological models as generality and comprehensiveness are achieved through consideration of additional ecological components and interactions.

71. At present, several large ecological models have been developed, many within the International Biological Program (IBP). Significant contributions are described in the following paragraphs.

Lakes

72. Several lake ecological models have been developed, including the Lake Texoma Cove Model,[80] CLEAN,[81] and WINGRA 2.[82] The Tundra and Coniferous Forest Biomes of the IBP have also developed models. Various versions of the lake ecological models simulate functional relationships such as phytoplankton dynamics,[73] macrophyte growth,[83] predator-prey biomass for fish,[84] aquatic carbon,[85] and nitrogen cycling.[86] Many of the models are modular in structure permitting the submodels to be coupled or operated independently. These models, however, are primarily single-point models and do not incorporate hydrodynamics. The CLEAN model does have a separate hydrodynamic circulation model, but it is not coupled with the ecological model.

73. A model developed by Chen and Orlob[64] and subsequently modified for the Hydrologic Engineering Center (HEC)[87] contains hydrodynamic and ecological subroutines. This model also permits the simulation of reservoir operation by including subroutines to handle withdrawal through the outlet works. The model is one-dimensional and therefore

averages constituent concentrations over the entire layers, but it does simulate water-quality constituents ranging from microorganisms to fish. Several modifications and improvements in the model have been made by WES, and an intensive research and development effort is ongoing as part of the Corps' Environmental Impact Research Program. Little confidence can be placed in the existing model for simulation of any biological trophic levels other than algae. With proper calibration, the existing model is useful for selected applications for simulation of the relative dynamics of temperature, D.O., nutrients (carbon, nitrogen, and phosphorus), and phytoplankton. Appropriate subroutines for simulating wind-mixing, ice cover, suspended solids, anaerobic conditions, and higher biological trophic levels are under development by WES and others, but presently are not available.

Streams

74. An interdisciplinary team of scientists at Michigan State University is formulating an operational model of a temperate zone woodland stream. A gross total ecosystem model has been developed,[88] but recent modeling emphasis has been placed on the precise description of detritus processing, the major energy source for small woodland streams.[89]

75. The major modeling effort within the Coniferous Forest Biome of the IBP was conducted at Oregon State University. The total ecosystem model conceptually is structured similarly to that proposed by Cummins at Michigan State University, but unique and significant contributions include a submodel for simulating periphyton dynamics.[90] The stream model developed in the Desert Biome differs from the woodland stream model in that autochthonous production is a significant energy source; this is characteristic of desert and grassland stream systems.

76. The modified version of the Chen and Orlob model also contains a stream model that is compatible with the lake ecological model.[87] The quality constituents are very similar in the two models. The model recently has been modified by the HEC to consider unsteady flow conditions. Various versions of the basic model have been modified to simulate braided channel situations, benthic algae, and toxicity;

however, the latter two subroutines must be considered as unverified first-cut approximations.

Marsh-estuarine systems

77. Few estuarine ecological models exist. However, a number of investigators studying the processes and pathways of nutrient flows in estuaries and marshes have recently employed mathematical modelers to develop models of estuarine nutrient dynamics. The lag in estuarine modeling, relative to other aquatic systems, largely reflects the impetus provided to stream and lake modeling by the IBP. Also, the lack of adequate two-dimensional hydrodynamic models of the marsh and stratified estuarine systems has resulted in less emphasis being placed on the development of appropriate ecological subroutines.

78. The marsh-estuarine models have generally been developed around the circulation of nutrients. Initial simulation models have been developed that characterize phosphorus dynamics in estuaries.[91] Preliminary models are also available for simulating nitrogen cycling and phytoplankton dynamics in marine systems.[92] These nitrogen models also characterize marine outfall and coastal upwelling ecosystems. Recently, efforts have been directed at characterizing and modeling the pathways and kinetics of carbon cycling in Georgia and North Carolina coastal marshes and estuaries. Zieman and Odum at the University of Virginia are conducting studies designed to develop a predictive model of marsh succession and production (DMRP Task 4A05). Saila has studied the effects of dredged material disposal in Rhode Island Sound, especially with respect to the recolonization of benthic organisms. He has done some development of a predictive model of benthic recolonization based on a species equilibrium model developed by MacAurthur and Wilson[93] from island biogeography.

Summary

79. In summarizing the review of mathematical ecological models, the following conclusions are drawn.

a. Detailed mathematical ecological models presently are not sufficiently developed to be applicable to problems associated with dredged material disposal, even for those applications requiring considerable ecological characterization. Additional research is needed to determine the need for reparameterization, the required accuracy and precision of input data, and the identification of residual, site-specific characteristics. The extensive data requirements needed for complete parameterization, estimates of initial conditions, and specifications of boundary conditions far exceed the capabilities of almost all specific project studies and most research programs.

b. Ecological modeling programs such as the IBP have provided the identification, measurement, and mathematical translation of numerous biological phenomena; the development of an extensive repertoire of modeling constructs; and the initial development of comprehensive ecological models. Some of these models represent an exhaustive inclusion of biological detail and can serve as a basis for further model evaluation and simplification.

c. The state of the art of mathematical ecological modeling is developing rapidly. While research efforts such as the IBP are increasing the complexity and resolution of the models, complementary research such as that being conducted at WES is aimed at modifying and verifying ecological models suitable for practical application to environmental problems associated with engineering activities.

PART V: APPLICATION OF ECOSYSTEM MODELING METHODOLOGIES TO DREDGED MATERIAL RESEARCH

Ecological Problem Areas

80. An analysis of the capabilities, limitations, and applications of simulated ecosystem modeling has revealed four general aspects of dredged material disposal for which existing modeling techniques would be useful or for which model development is recommended. These areas are land and confined disposal, habitat creation, open-water disposal, and pollution criteria development. Within each area, basic categories of ecological problems have been identified and are tabulated in Table 1. Because many of the problems are common to more than one area, the problems are discussed sequentially and Table 1 must be used to associate the discussions with the appropriate areas. This discussion was not organized by the specific tasks outlined for DMRP technical planning because similar recommendations would apply to more than one task. Table 1 does not attempt to address the question of what level or specific types of research are justified for various problems. This will be addressed to some extent in the narrative of this part of the report. Recommendations in Table 1 do suggest that modeling techniques are available and probably are needed to provide an adequate understanding and the predictive capability required to address several of these potential problem areas. The modeling approaches recommended are applicable and feasible at least with a reasonable amount of adaptation and development.

81. In no case is modeling an end unto itself, and in every case it should be used only as one of the tools employed to solve a problem. Results of field studies should be involved at some stage in all modeling efforts--mathematical or physical. This involvement should occur both in model formulation and in model evaluation or verification.

Applicability of Physical Modeling

82. Physical ecosystem modeling techniques generally are

applicable and should be used to aid in interpreting and applying results of field studies, to understand and quantify processes that cannot be adequately studied under field conditions, and to serve as data generators for the development and evaluation of certain types of mathematical models.

83. Physical models are most appropriate where the processes and interactions within a system are not adequately known or quantified to be expressed mathematically. Physical ecosystem modeling uses a "black box" approach to circumvent this lack of understanding. What are hoped to be the important components of a natural system are placed under suitable, controlled, environmental conditions to form the black box. The research objective is either to investigate the black box to understand its internal structure and function, or to perturb the experimental system and observe the response in order to evaluate the potential effects of the perturbation on a natural system. Therefore, physical ecosystem models may be used to simulate aspects of natural systems that, to some extent, are not understood. However, they must be operated essentially at real-time rates, and there is always a danger that experimental conditions could produce distortions in the quality or quantity of the system's behavior. In almost all cases, physical modeling increases the understanding of the system being modeled.

Applicability of Mathematical Modeling

84. Mathematical ecosystem modeling techniques are generally applicable and should be used to provide a systems approach to organizing research, to provide a means of summarizing and analyzing large amounts of data and complex interactions with many components, and to aid in predicting future events.

85. The process of mathematical modeling also tends to increase our understanding of the system being modeled, but a mathematical model *per se* is only as good as the existing understanding of the structure and the function of the system that served as a basis for model formulation. Advantages of mathematical modeling are in organizing current

understanding of the structure and function of ecosystems and in expressing this understanding in a form which can be solved by computer to make rapid predictions. Therefore, mathematical models can be applied most appropriately where the important basic processes and interactions of these processes are adequately understood and quantified to be expressed mathematically. Unfortunately, many of the ecological aspects of natural systems do not fall into this category. Conceptual models should be used to guide research to provide understanding and quantification. However, it is recommended that efforts to develop mathematical models should be initiated only in areas where the existing state of the art is such that most of the important processes are understood and an adequate data base suitable for modeling is essentially established. It is felt that developmental efforts, in cases where the understanding and data base do not exist, would exceed the time frame of the DMRP.

Application to Colonization and Ecological Succession

86. The particular species that will colonize a barren environment or new habitat and the pattern of ecological succession that follows as the biological community changes species composition are determined by the species that are available to invade the area and by the individual tolerances of the various species to environmental conditions. Dominance of the "fittest" occurs through competition for space and resources and through inherent differences in abilities to survive stresses of the physical environment. As the environment changes, either by outside perturbation or by internal biological activity, environmental conditions may become more favorable for new invaders or minority species than for the dominant species of the existing community.

Physical modeling

87. A detailed characterization of colonization and ecological succession using physical models is not feasible since succession is defined over long time intervals and since biological processes cannot be accelerated substantially in physical models. However, microcosms may be used to investigate certain aspects of succession, such as screening

substrate types to determine their suitability for supporting selected organisms and for determining the tolerance limits of organisms to various environmental variables.

Mathematical modeling

88. Drs. Zieman and Odum of the University of Virginia, in a DMRP contract effort with WES, are attempting to develop a mathematical model of ecological succession and production in estuarine marshes and on dredged material. The development of mathematical models for these environments may be feasible since diversity of plant species is low and physical factors play a significant role in successional phenomena. Furthermore, empirically determined relations between physicochemical conditions and the presence of plant species may be adequate to predict successional patterns given the time series behavior of the dominant physicochemical parameters. However, even in these cases mathematical models can reflect only the existing understanding and quantification of the system, and these models should be expected only to predict the general successional trends of dominant species. Furthermore, the acquisition of adequate data to characterize the time series behavior of important physicochemical variables for a variety of types of coastal systems will be necessary before the model will have widespread utility.

89. For environments in which diversity is high or where the biological community significantly modifies the physicochemical environment, modeling successional phenomena requires consideration of many species and specification of the mechanisms of many complex interactions. Modeling detailed successional phenomena in these diverse environments is not considered feasible within the existing state of the art.

90. There is a possibility that the "equilibrium species" model developed by MacArthur and Wilson[93] or some similar approach could be adapted for use in simulating recolonization of open-water dredging and dredged material disposal sites by benthic organisms. However, the lack of an adequate data base and the diversity of organisms and habitats make this task more difficult than the development of a successional model for marsh grasses. Some of the basic data required for this benthic model could be obtained by microcosm studies.

Application to Species Diversity

91. The diversity of species in an ecological community is generally recognized as being positively correlated with ecological stability. This seems valid since a greater diversity implies a larger gene pool, a greater range of environmental tolerances, more mechanisms for homeostatic feedback within the system, and a larger number of food chains through which energy can flow and materials can cycle. High species diversity is generally considered to be ecologically desirable and indicative of a relatively stable, healthy environment. Therefore, species diversity frequently is selected as a parameter for assessing the ecological impact of an environmental perturbation.

92. Because species diversity is a measure of biological complexity, adequate physical and mathematical modeling of species diversity is not feasible within the existing state of the art. Simplification of prototype systems to enable one to physically or mathematically simulate the system necessitates a simplification in community structure and the establishment of boundary conditions. Once boundary conditions for the model are established, the natural phenomenon of invasion of new species only can be simulated by planned introductions. While obvious invasions of well known dominant species may be anticipated and incorporated in the simulation, the diversity of lesser known species and their competitive interactions presently cannot be adequately modeled.

93. Relationships between species diversity and ecological stability have been theorized but not adequately documented. C. S. Holling (University of British Columbia) has proposed the concept of ecological resiliency as the appropriate ecological yardstick for resource planning rather than diversity and stability. In fact, the three concepts are very closely interrelated; yet they remain unquantifiable in a practical sense in the field. Diversity indices and other techniques are useful indicators when measured and interpreted properly. However, the relative contributions and importance of "evenness" (the distribution of individuals among species) and "diversity" (the number of species present) must be assessed for these indices to be meaningful. The role of these

two components of species diversity in biological community structure and in ecological stability is undefined. At present it is not known how to extrapolate quantitatively changes in simplified simulations of diversity to prototype systems.

Application to Biological Productivity

94. Biological productivity is generally broadly defined. For larger plants and animals, it usually refers to the net accumulation of biomass per unit of time, normally estimated directly by changes in standing stock. For total biological communities, net productivity is equal to gross productivity minus total community respiration after import and export are taken into account. Estimates of community metabolism are usually based on indirect measurements, such as monitoring changes in concentrations of common metabolic reactants such as oxygen or carbon dioxide. Techniques for measuring community metabolism include *in situ* monitoring, the use of bottles (aquatic communities) and tents (terrestrial communities) to isolate a portion of the community, and the use of radioactive tracers such as ^{14}C and ^{32}P. Productivity estimates may vary by an order of magnitude, depending on the method of measurement, and there is controversy in the literature over methodologies. Furthermore, diurnal variations in respiration rates for various organisms have been observed, but the causes and mechanisms of these patterns are not adequately known. Consequently, modeling of total community metabolism is difficult, and at best it involves some gross approximations. However, community metabolism is a useful parameter and worthy of study since it summarizes in one estimate an expression of the overall functioning of a biological community.

Physical modeling

95. Physical ecosystem simulations can be used to evaluate the relative effects of dredged material disposal on the overall metabolism of biological communities whose metabolism is dominated by organisms whose size and functional behavior make them suitable for study in confined experiments. Salt marsh, planktonic, and benthic communities are examples which meet this criterion. The metabolism of large or mobile

species cannot be evaluated adequately in artificial environments. However, they usually do not display a significant role in overall community metabolism except in some terrestrial and man-made environments. If quantitative results are desired, close simulation or use of natural light regimes and simulation of natural turbulence levels and allochthonous nutrient fluxes are essential. Therefore, SEM's technically are more suitable for these studies than are microcosms.

96. WES contracted Dr. James Gosselink, Louisiana State University, to investigate the physiological response of marsh plants to environmental stress (DMRP Task 4A06). Physiological response in this study is being measured by changes in productivity. The objective of the study is not to estimate productivity of marsh ecosystems, but to characterize relationships between selected environmental variables and plant response. Similar studies are needed to evaluate the productivity of selected types of benthic organisms and important marsh grass species on various types of dredged material. For purposes of comparing substrates on a relative basis, a factorial arrangement of treatments using microcosms as experimental units would be an appropriate research approach.

97. The importance of marsh-estuarine ecosystems to the ecology of the coastal zone is commonly accepted. Generally, there is believed to be a mutualistic interaction between estuaries and surrounding marshes. Despite the significant number of field studies that have been conducted on these systems through the years, the nature and importance of many of these interdependencies remain undefined or unquantified. Tidal-driven fluxes of the products of biological productivity and their degradation products in the form of detritus, planktonic biomass, and dissolved organic compounds between marshes and estuaries are not adequately understood. Without additional understanding, it is impossible to predict the long-term consequences of alterations to these fluxes by dredged material disposal in either marshes or estuaries.

98. WES developed design concepts for SEM's of marsh-estuarine ecosystems suitable for evaluating effects of dredged material disposal on marsh-estuarine productivity (DMRP Tasks 1D08 and 4A09). Initial designs and pilot experiments indicate that these models represent a

feasible research approach for understanding and predicting effects of engineering activities on several aspects of coastal ecology.

Mathematical modeling

99. Mathematical models simulating the productivity of terrestrial and aquatic ecosystems have been developed, but their adequacy for application and problem solving has not been adequately demonstrated. Typically, productivity is simulated using phytoplankton models in aquatic systems and using analogous models for terrestrial systems. The major factors regulating productivity have been identified and their mode of action sufficiently investigated to enable the development of low-resolution models that may be used to predict major changes in productivity. For those environments for which succession models are applicable, changes in productivity resulting from altered dominant species may be predicted. Productivity models for confined land disposal sites and newly created habitat areas may be feasible to develop but presently are not available. If mathematical model development other than colonization and succession is undertaken, emphasis should be on developing ecological models with appropriate subroutines to generate estimates of productivity rather than developing additional productivity models *per se*. The resulting models would be more suitable than existing productivity models for including subtle factors affecting productivity, such as uptake and bioaccumulation of toxic and stimulatory materials and species interactions.

100. Although development of more comprehensive ecological models suitable for simulating the effects of dredged material disposal in selected environments may be feasible, it is suggested that successful development of such models is outside the existing time frame of the DMRP. However, it is strongly recommended that conceptual ecological models be used to guide field monitoring efforts, scaled ecosystem modeling, and laboratory studies so that the resulting data will be useful for future model development.

101. Drs. George Hornberger and Mahlon Kelly, University of Virginia, under contract to WES (DMRP Task 1D08), have developed computer programs to perform oxygen budget analyses for rivers, nonstratified

standing waters, and a one-dimensional analysis for stratified waters. The programs compute primary productivity and community respiration as a function of time from changes in D.O. concentrations after correction for reaeration and advection. The technique involves an exact solution to the oxygen mass-balance equation using a Fourier series analysis of D.O., temperature, and flow data. All three programs presently are operational on the computer system at WES.

Application to Material Cycling

102. Material cycling includes the cycling of nutrients, heavy metals, pesticides, and other materials among the biotic and abiotic components of ecosystems. Recent investigations of material cycling have resulted in many hypothesized mechanisms, pathways, and the recognition of numerous inadequacies in the present knowledge of ecosystem function. Most environmental problems are addressable through consideration of material cycling; however, a detailed understanding of material cycling implies a detailed understanding of almost all aspects of ecosystem functioning.

Physical modeling

103. Microcosms and SEM's are appropriate research approaches for investigating the uptake and bioaccumulation of materials. The concepts and operational methodologies of these approaches are sufficiently developed to enable adaptation to a number of specific problems and systems. SEM's may be used to study the effects of material transport between ecosystems such as between a land disposal site and an adjacent aquatic system. Additional uses of microcosms and SEM's to characterize material cycling include assistance in understanding basic processes, the identification of pathways of material cycling, and as aids in the development and verification of mathematical models.

104. A number of studies are ongoing within the DMRP in which laboratory simulation techniques are being used in part to investigate selected aspects of material cycling. These studies include:

a. Study of Eh, pH, and D.O. effects on chemical constituent migration during open-water disposal of dredged material, conducted by Dr. W. H. Patrick, Jr., Louisiana State University (DMRP Task 1C04).

b. Survey of the release of pesticides into the water column during dredging and disposal, conducted by Envirex, Inc., Milwaukee, Wisconsin (DMRP Task 1C04).

c. Effects of dispersion, settling, and resedimentation on migration of chemical constituents during open-water disposal of dredged material, conducted by Drs. K. Y. Chen and T. F. Yen, University of Southern California, Los Angeles, California (DMRP Task 1C06).

d. Study of the availability of sediment-adsorbed heavy metals to benthos, with particular emphasis on deposit feeding infauna, conducted by Texas A&M University (DMRP Task 1D06).

e. Study of the availability of sediment-adsorbed pesticides (DDT, chlordane, malathion) to benthos, with particular emphasis on deposit feeding infauna, conducted by LFE Environmental Analysis Labs, Richmond, California (DMRP Task 1D07).

105. SEM's similar to those designed at WES as part of DMRP Tasks 1D08 and 4A09 are suitable for investigating many aspects of material cycling between marsh and estuarine ecosystems. Mass-balance and radioactive tracer techniques are available for studying these fluxes. Treatment versus controls should be used in comparing natural marshes with marshes created with dredged material. Treatment versus control simulations also are suitable for evaluating vegetative uptake of heavy metals and other contaminants from dredged materials disposed in marsh and upland habitats.

Mathematical modeling

106. The mathematical simulation of material cycling for the prediction of the effects of selected contaminants on selected biological systems is feasible at a useful level of resolution. However, existing models would require further development to be applicable to the prediction of environmental impacts resulting from dredging and disposal operations. Mathematical models for evaluating nonconservative material cycling presently are suitable only for studying a single point in space or a one-dimensional gradient. Incorporation with or use in conjunction with sediment-transport models would be necessary for studying

open-water disposal of dredged material. Many of the pathways and mechanisms for cycling of materials within complex ecosystems are undefined, and fluxes between ecosystems (e.g. marshes and estuaries) are not adequately quantified. Consequently, existing mathematical ecological models would require adaptation and should be applied with caution even for limited purposes where only relative evaluations are desired.

Application to Artificial Establishment Techniques for Habitat Creation

Physical modeling

107. Insights into the environmental requirements of desirable plant and animal species and the selection of techniques for artificial establishment of relatively immobile organisms on dredged material may be determined in the laboratory using physical models at a cost considerably less than in field studies. Initial efforts should be directed at evaluating environmental requirements and establishment techniques for important marsh grass species. Microcosms located in controlled environments are appropriate for evaluating the survival and growth of selected marsh grasses on various types of dredged material (such as sand, silt, clay, polluted, and unpolluted) at various stages of consolidation. SEM's with realistic tidal regimes and turbulence levels appear suitable for evaluating various marsh grass propagules and establishment techniques on various substrates. These types of studies could be conducted in the field, but difficulties would occur in setting up and maintaining the variety of treatment combinations and in obtaining interpretable results without adequate environmental and experimental controls. It is recommended that these various treatments be evaluated on a small scale under controlled conditions prior to selecting the most feasible techniques and substrates for field testing. Tapering hydraulic flumes that could be operated and calibrated to give known gradients of bed shear stress also could be used to evaluate the ability of various marsh grass propagules to withstand selected tidal and wave energies.

Mathematical modeling

108. Mathematical modeling generally is considered inappropriate

for developing and evaluating artificial establishment techniques.

Application to Direct Smothering of Benthic Organisms

Physical modeling

109. The investigation of the direct effects of sediment deposits on benthic communities may be studied effectively in microcosms. A study under the direction of Dr. D. L. Maurer, University of Delaware (DMRP Task 1D03), is being conducted to determine the vertical migration ability and survival of benthos covered by dredged material deposits. The results of this study should be evaluated prior to initiating other microcosm studies in this area.

Mathematical modeling

110. Mathematical modeling is not suitable for addressing this objective.

Application to Oxygen Budget Analysis

111. Dissolved oxygen is a critical environmental parameter that is relatively easy to monitor in the field. Existing D.O. mathematical models may be adapted to predict potential D.O. depression due to dredged material disposal in nonstratified aquatic environments. However, for greater resolution of the sources and sinks of D.O. and for studying mildly perturbed environments, D.O. models need further development, particularly for anaerobic conditions. Under stratified and nonsteady flow conditions, additional model development is also needed for reliable predictions. As good two-dimensional hydrodynamic models are developed, adequate D.O. subroutines can be incorporated.

112. The computer programs developed by the University of Virginia for WES (DMRP Task 1D08) and described previously in this report as tools for calculating aquatic community metabolism are suitable for making a detailed oxygen budget analysis of observed data from any aquatic environment where advection and reaeration can be defined.

Application to Pollution Criteria Development

Background and problems

113. The enactment of legislation regulating the disposal of wastes and dredged material in the oceans (Public Law 92-532) and inland waters (Public Law 92-500) required the EPA, in conjunction with the Corps of Engineers, to develop guidelines for dredged material disposal.[94] Guidance, which was developed through these cooperative efforts, has been published in the Federal Register. (For guidance on PL 92-532, see Vol 38, No. 198, 15 October 1973; for PL 92-500, see Vol 40, No. 173, 5 September 1975.)

114. Sediments contain constituents that exist in different chemical forms and are found in various concentrations in several locations within the sediment. Methods to predict the pollution potential of dredged material should only consider contaminants in sediment fractions that are available for affecting water quality and the associated biota. Regulatory criteria should differentiate that fraction of a sediment that does not have an adverse effect on the environment from that fraction that does.[94]

115. The "Elutriate Test" has been selected as one of the criteria to be used in determining the pollution potential of dredged material. The technique indicates those constituents in the interstitial water and those ions loosely bound to the ion fraction that would be readily available for immediate impact on water quality and aquatic organisms. It also may have some value in predicting constituent concentrations in the interstitial water fraction of deposited dredged material. However, rather than providing hard criteria, the test simply provides indicators of potential problems. Furthermore, the test only provides estimates of the amount of various chemical constituents that may be readily released into receiving waters. The amounts actually released or taken up by dredged material following open-water disposal, the effects of the quality of the receiving waters on the availability and effects of the released constituents, and the actual ecological

effects of various concentrations and forms of released chemicals are not adequately known.

116. Lee and Plumb have pointed out that a variety of factors could affect the results of the elutriate test and that considerable research is needed to evaluate the significance of these factors in influencing the test for a wide variety of sediments.[95] Studies could be conducted to determine meaningful relationships between elutriate test results and environmental quality. Various field studies have indicated that suitable laboratory studies are needed to adequately evaluate the effects of sediment disposal on biota.[96,97] Simple bioassay experiments have been useful in indicating some direct effects of Great Lake Harbor sediments on benthos and plankton.[98]

117. Several ongoing research studies sponsored by the DMRP are designed to address various problems associated with developing dredged material disposal criteria. Work under the direction of Dr. G. F. Lee, University of Texas at Dallas (DMRP Task 1E03A), is designed to evaluate factors affecting the elutriate test and to investigate bioassay procedures. Wapora, Inc., Washington, D. C. (DMRP Task 1D02), has conducted an assessment of the equipment, methodologies, and institutional capabilities available for conducting or developing bioassays. The Environmental Effects Laboratory at WES is conducting a study to determine the partitioning of a variety of elements within various types of sediment based on selective extraction techniques (DMRP Task 1E04) and is conducting bioassays to assess the validity of the elutriate test (DMRP Task 1E06).

Physical modeling

118. Bioassays and microcosms are appropriate research tools to apply in developing and evaluating meaningful pollution criteria. Additional studies need to be conducted to provide applicable biological interpretation and to establish relationships among sediment elemental partitioning, elutriate and residue portions of the elutriate test, and their effects on biological communities. Treatments to simulate a typical range of perturbations at various distances from the disposal site should be established under approximately natural levels of temperature,

light, turbulence, and D.O. Emphasis should be placed on simulating realistic time-concentration relationships so that effects of contaminants observed in bioassays can be extrapolated to field situations.

119. It is recommended that evaluations of effects in pelagic zones be limited to algae and selected invertebrates, since more mobile species probably can escape the disposal plume. Although effects of open-water disposal on the pelagic zone probably are considerably less important than effects on benthic communities, effects on planktonic organisms may be more readily measured and correlated with the elutriate test. Development of meaningful benthic bioassays for dredged material will be difficult, but this task should be given high priority. Studies with benthic communities should include representatives of the meiofauna and selected economically important species of macrofauna, including some juvenile forms. These studies not only should provide useful guidance for pollution criteria development and evaluation, but also should aid in interpreting field observations made during longer term monitoring studies at selected disposal sites.

Mathematical modeling

120. Application of mathematical chemical models to criteria development offers some potential but additional development would be required. Chemical equilibrium models used in conjunction with a sediment transport model might offer some utility for predicting water quality at the disposal site if sufficient data on the disposal site prior to disposal and the dredged material slurry were available as model input. However, additional research would be needed on diffusional transport processes before these models could be considered reliable tools. Chemical equilibria models being developed at California Institute of Technology under the direction of Dr. J. J. Morgan[51,55] offer some potential for adaptation and application.

121. A number of mathematical D.O. models are available for one-dimensional analysis of D.O. demands imposed on receiving waters by dredged material. These models, along with some of the existing phytoplankton and ecological models, would be useful in evaluating criteria and predicting general system responses to changes in selected

parameters. Presently, these parameters include temperature, pH, alkalinity, dissolved solids, D.O., organic loading, and various forms of nitrogen and phosphorus. In general, the existing models do not adequately simulate toxicity resulting from contaminants such as heavy metals and pesticides.

PART VI: SUMMARY

122. This report addresses the applicability of ecosystem modeling methodologies to environmental problems associated with dredging and disposal operations. The objective of the study was to provide an assessment of the usefulness of physical and mathematical ecological modeling techniques in the DMRP. The report may be of value to field offices by providing a basic introduction to various modeling techniques and recommendations for the application of these techniques to various types of environmental problems.

123. The introduction of new modeling techniques and the application of existing models to different problems proceed rapidly. Because of the relatively long lag between the preparation of this report and publication, many of the studies described as current have been completed and published and other relevant research has been initiated.

124. Current research and modeling achievements were evaluated through literature review and discussions with recognized authorities. It became apparent early in the study that the concepts and terminology associated with laboratory and physical modeling approaches varied significantly. This fact required that a clarification of these models be presented prior to discussing their feasibility for addressing environmental problems.

Physical Modeling

125. Physical modeling approaches used in ecological research include bioassays, microcosms, and SEM's. Bioassays currently are used most frequently to indicate the potential biological response from a given strength of stimulus, such as a nutrient or pesticide. Microcosms are used to study ecosystem processes and responses to perturbation where some environmental variables (e.g. light, temperature) can be controlled and ecosystem boundary conditions can be defined. SEM is an extension of the microcosm concept where important physical processes (e.g. mass, momentum, and energy transport) as well as biological and

chemical considerations are incorporated into model design.

126. Physical ecosystem modeling techniques generally are applicable and should be used in the DMRP to understand and quantify effects of environmental perturbations which cannot be adequately studied under field conditions, to serve as data generators and test systems for the development and evaluation of certain types of mathematical models, and to aid in designing and interpreting results of field studies.

127. Physical models are most appropriate where processes and interactions within a system are not adequately understood or quantified to be expressed mathematically or where the resulting mathematical relationships are unsolvable with present numerical techniques. Physical modeling provides a "black box" approach for circumventing deficiencies in total system understanding required for mathematical modeling and provides definable and controlled conditions under which system responses to perturbations can be studied in an interpretable manner.

Mathematical Modeling

128. With the exception of some basic D.O. models, few applications of mathematical models to ecological problems have been attempted past model development. A survey of these models provided insight into those aspects of environmental problems which can be addressed by modeling.

129. Four classes of mathematical water-quality and ecological models that may be applicable to the DMRP have been identified: (a) D.O. models, (b) chemical models, (c) phytoplankton models, and (d) ecological models. D.O. models emphasize the simulation of temporal and/or spatial variations in D.O. Chemical models describe with considerable resolution the reactions among chemical species in aquatic environments. Phytoplankton models address problems of excessive growth of often undesirable species of microscopic plants. Ecological models are characterized by their comprehensive inclusion of numerous species or paraspecies and by their emphasis on describing food chain or species interactions with their environment.

130. Mathematical modeling techniques should be used in the DMRP to provide a means of summarizing and analyzing large amounts of data and complex interactions with many components and to aid in making predictions of future events. A mathematical model _per se_ is only as good as the understanding of the structure and function of the prototype ecosystem, but the process of modeling usually does increase the understanding of the system.

131. Mathematical modeling can be applied where the assumptions necessary for model development are not excessively limiting. Unfortunately, many of the important ecological processes and interactions occurring in natural systems are too poorly understood and inadequately quantified to be expressed mathematically. Model calibration and verification are extremely important and are common weaknesses of ecological modeling efforts. Since no existing mathematical ecological model is entirely mechanistic, the achievement of reasonable agreement between model simulation and prototype behavior for a given set of conditions does not constitute an adequate verification; they may or may not respond similarly to a different set of conditions such as a significant environmental perturbation.

132. It is recommended that development of mathematical models should be initiated within the DMRP only in cases where the existing state of the art is such that most of the important processes are understood and an adequate data base for model development, verification, and use is established. In other cases, successful development would exceed the time frame of the DMRP.

Considerations for Use of Models in Dredged Material Research

133. In no case should modeling be an end unto itself, and in every case modeling should be used only as one of the tools employed to solve an environmental problem. Results of field studies must be involved at some stage in all modeling efforts--mathematical and physical. This involvement should occur both in model formulation and in model evaluation or verification. Conceptual models (e.g. compartment models)

should be developed to guide all laboratory and field research so that results are more likely to be useful for future mathematical model development.

134. The review of ecosystem modeling approaches has revealed that few applications have been made to specific environmental problems related to dredging and disposal operations. Environmental problems identified as pertinent to the DMRP are so complex that the most effective research approach to their solution often should include concurrent laboratory, field, and modeling studies. Specific modeling approaches are appropriate and are recommended for the following problems and research needs associated with dredged material disposal: colonization and ecological succession, biological productivity, material cycling, artificial establishment techniques for habitat creation, direct smothering of benthic organisms, oxygen budget analysis, and pollution criteria development.

135. The choice of a specific modeling approach depends on the particular environment, the method of dredging and disposal, and the dredged material's characteristics. In most cases, existing models will require modification, adaptation, and verification before being applied with confidence. Ecological modeling techniques are so complex that the existing state of the art is not feasible for application to routine and small project evaluations. Large projects which may result in significant environmental perturbations may warrant application of these more extensive evaluation approaches. It is suggested that Corps field offices anticipating a need for applying ecological modeling techniques contact the WES for current information and more specific guidance.

REFERENCES

1. Lawrence, D. R. and Bacharach, A. L., Evaluation of Drug Activities: Pharmacometrics, Vol 1, Academic Press, London, 1964.

2. Burdick, G. E., "Use of Bioassays in Determining Levels of Toxic Wastes Harmful to Aquatic Organisms," Transactions, Symposium on Water Quality Criteria to Protect Aquatic Life, American Fisheries Society, Supplement, Special Publications No. 4, Vol 96, No. 1, 1967.

3. Lee, G. F., "Review Paper - Chemical Aspects of Bioassay Techniques for Establishing Water Quality Criteria," Water Research, Vol 7, No. 11, 1973, pp 1525-1546.

4. Beyers, R. J., "The Microcosm Approach to Ecosystem Biology," The American Biology Teacher, Vol 26, No. 7, 1964, pp 491-498.

5. Taub, F. G., "A Biological Model of a Freshwater Community: A Gnotobiotic System," Limnology and Oceanography, Vol 14, No.1, 1969, pp 136-142.

6. McIntire, C. D., "A Laboratory Approach to the Study of the Physiological Ecology of Benthic Algal Communities," Proceedings, Eutrophication-Biostimulation Assessment Workshop, 1969, pp 146-157.

7. DeVen, W. A., "Design and Construction of a Saltwater Environment Simulator," Working Paper No. 71, 1970, Federal Water Pollution Control Administration, Pacific Northwest Water Laboratory, Corvallis, Oreg.

8. Cooper, D. C. and Copeland, B. J., "Responses of Continuous-Series Estuarine Microecosystems to Point-Source Input Variations," Ecological Monographs, Vol 43, No. 2, 1973, pp 213-236.

9. Copeland, B. J. and Wohlschlag, D. E., "Biological Responses to Nutrients-Eutrophication: Saline Water Considerations," Advances in Water Quality Improvement, University of Texas Press, Austin, Tex., 1968, pp 65-82.

10. Margalef, R., "Laboratory Analyses of Estuarine Plankton Systems," Estuaries, Horn-Shafer, Baltimore, Md., 1967, pp 515-524.

11. Odum, H. T., et al., "Experiments with Engineering of Marine Ecosystems," Marine Science Publications, No. 9, 1963, pp 373-403.

12. Odum, H. T. and Chestnut, A. Z., "Studies of Marine Estaurine Ecosystems Developing with Treated Sewage Wastes," NSF Sea Grants No. GS-18, Annual Report 1969-1970, North Carolina State University, Raleigh, N. C.

13. Cummins, D. W. et al., "Organic Enrichment with Leaf Leachate in Experimental Lotic Ecosystems," Biological Science, Vol 22, No. 12, 1972.

14. Phinney, H. K. and McIntire, C. D., "Effect of Temperature on Metabolism of Periphyton Communities Developed in Laboratory Streams," Limnology and Oceanography, Vol 12, 1965, pp 341-344.

15. Kevern, N. R. et al., "Use of Artificial Substrata to Estimate the Productivity of Periphyton," Limnology and Oceanography, Vol 11, No. 4, 1966, pp 499-502.

16. McIntire, C. D. and Phinney, H. K., "Laboratory Studies on Periphyton Production and Community Metabolism in Lotic Environments," Ecological Monographs, Vol 35, 1965, pp 237-258.

17. Kevern, N. R. and Ball, R. C., "Primary Productivity and Energy Relationships in Artificial Streams," Limnology and Oceanography, Vol 10, No. 1, 1965, pp 74-87.

18. McIntire, C. D. et al., "Primary Production in Laboratory Streams," Limnology and Oceanography, Vol 9, 1964, pp 92-102.

19. Symons, J. M. et al., "Impoundment Influence on Water Quality," Journal, American Water Works Association, Vol 57, No. 1, 1965, pp 51-75.

20. __________, "Enhancing Biodegradation of Synthetic Organics in Stratified Impoundments by Artificial Modification of the Thermal Profile," Proceedings, Symposium of Garda, International Association of Scientific Hydrology, Vol 1, Publication No. 70, 1966.

21. Symons, J. M., Irwin, W. H., and Robeck, G. G., "Impoundment Water Quality Changes Caused by Mixing," Journal, Sanitary Engineering Division, American Society of Civil Engineers, Vol 93, No. SA2, Apr 1967, pp 1-20.

22. Barren, C. F. and Howlett, H. A., "Delaware River Basin Commission - Pumped Storage Operation and the Spawning Fish," Proceedings, International Conference on Pumped Storage Development and Its Environmental Effects, 1971.

23. Harleman, D. R. F., Fisher, J. S., and Thatcher, M. L., "Unsteady Salinity Intrusion in Estuaries," July 1974, Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Massachusetts Institute of Technology, Cambridge, Mass.

24. Keeley, J. W., A Feasibility Study of a Laboratory Model as a Research Tool for Impoundment Water Quality Investigations, Ph. D. Dissertation, 1971, University of Oklahoma, Norman, Okla.

25. Odum, H. T. and Hoskin, C. M., "Comparative Studies of the Metabolism of Marine Waters," Publications of the Institute of Marine Science, University of Texas, Vol 5, 1958, pp 16-46.

26. McConnell, W. J., "Productivity Relations in Carboy Microcosms," Limnology and Oceanography, Vol 7, No. 3, 1962, pp 335-343.

27. Beyers, R. J., "Relationship Between Temperature and the Metabolism of Experimental Ecosystem," Science, Vol 136, No. 3520, 1962, pp 980-982.

28. Beyers, R. J., "The Metabolism of Twelve Laboratory Microecosystems," Ecological Monographs, Vol 33, No. 4, 1963, pp 281-306.

29. __________, "A Characteristic Diurnal Metabolic Pattern in Balanced Aquatic Microcosms," Publications of the Institute of Marine Science, University of Texas, Vol 9, 1963, pp 19-27.

30. Odum, H. T. and Hoskin, C. M., "Metabolism of a Laboratory Stream Microcosm," Publications of the Institute of Marine Science, University of Texas, Vol 4, 1957, pp 115-133.

31. Falco, J. W. and Sanders, W. M., III, "A Physical Model for Simulation of Aquatic Ecosystems," Modeling the Eutrophication Process, Proceedings, Workshop held at Utah State University, Logan, Utah, Nov 1973, pp 159-169.

32. Eley, R. L., Falco, J. W., and Kirby, C. J., "The Role of Physical Modeling in Marsh-Estuarine Mineral Cycling Research," Mineral Cycling in Southeastern Ecosystems, ERDA Symposium Series, CONF-740513, 1975, pp 166-178.

33. Tracor, Inc., "Estuarine Modeling: An Assessment," Technical Report, Project 16070DZV, Contract 14-12-551, Feb 1971, Water Quality Office, Environmental Protection Agency, Austin, Tex.

34. Birkhoff, G., Hydrodynamics: A Study in Logic, Fact, and Similitude, Dover, New York, 1955.

35. Streeter, H. W. and Phelps, E. B., "A Study of the Pollution and Natural Purification of the Ohio River, Factors Concerned in the Phenomena of Oxidation and Reaeration," Bulletin 146, 1925 (reprinted 1958), U. S. Public Health Service, Washington, D. C.

36. Stochastics Incorporated, "Stochastic Modeling for Water Quality Management," Water Pollution Control Research Series 16090 DUH 02/71, Feb 1971, Federal Water Quality Administration, Environmental Protection Agency, Blacksburg, Va.

37. Texas Water Development Board, "Simulation of Water Quality in Streams and Canals," DOSAG-1, Sep 1970, Austin, Tex.

38. __________, "Simulation of Water Quality in Streams and Canals; Theory and Description of the QUAL-1 Mathematical Modeling System," Report No. 128, Aug 1971, Austin, Tex.

39. Callaway, R. J., Byram, K. V., and Ditsworth, G. R., "Mathematical Model of the Columbia River from the Pacific Ocean to Bonneville Dam; Part I. Theory, Program Notes, and Programs," 1969, Coastal Pollution Research Program, Environmental Protection Agency, Corvallis, Oreg.

40. Callaway, R. J. and Byram, K. V., "Mathematical Model of the Columbia River from the Pacific Ocean to Bonneville Dam; Part II. Input-Output and Initial Verification Procedures," 1970, Coastal Pollution Research Program, Environmental Protection Agency, Corvallis, Oreg.

41. Dixon, N. P. et al., "Developing a Hydro-Quality Simulation Model," Report No. PRWG67-1, Jun 1970, College of Engineering, Utah State University, Logan, Utah.

42. Feigner, K. D. and Harris, H. S., "Documentation Report, FWQA Dynamic Estuary Model," Jul 1970, U. S. Department of the Interior, Federal Water Quality Administration, Washington, D. C.

43. Leendertse, J. J. and Gritton, E. C., "A Water-Quality Simulation Model for Well Mixed Estuaries and Coastal Seas: Vol III, Jamaica Bay Simulation," Report 4-709-NYC, Jul 1971, The Rand Corporation, New York, N. Y.

44. Shindala, A., Zitta, V. L., and Corey, M. W., "Water Quality Models for the Pascagoula River Basin, II. Tidal Estuaries," 1973, Engineering and Industrial Research Station, Mississippi State University, Starksville, Miss.

45. Bella, D. A., "Dissolved Oxygen Variations in Stratified Lakes," Journal, Sanitary Engineering Division, American Society of Civil Engineers, Vol 96, No. SA5, Oct 1970, pp 1129-1146.

46. Markofsky, M. and Harleman, D. R. F., "A Predictive Model for Thermal Stratification and Water Quality in Reservoirs," Report No. 134, Jan 1971, Department of Civil Engineering, Massachusetts Institute of Technology, Ralph M. Parsons Laboratory for Water Resources and Dynamics, Cambridge, Mass.

47. Carroll, W. E. and Fruh, E. G., "Hypolimnetic Dissolved Oxygen Simulation Model," Technical Report No. 87, Feb 1972, pp 6.1-6.19, Center for Research in Water Resources, University of Texas, Austin, Tex.

48. Falls, C. P., Chemical Equilibria and Dynamics of Keystone Reservoir, Ph. D. Dissertation, 1969, Oklahoma State University, Stillwater, Okla., p 147.

49. Eley, R. L., Physiochemical Limnology and Community Metabolism of Keystone Reservoir, Oklahoma, Ph. D. Dissertation, 1969, Oklahoma State University, Stillwater, Okla., p 240.

50. Falls, C. P. and Varga, L. P., "Chemical Equilibria Models of Lake Keystone, Oklahoma," Environmental Science and Technology, Vol 7, No. 4, 1973, pp 319-327.

51. Morel, F., McDuff, R. E., and Morgan, J. J., "Modeling of Adsorption of Solutes on Solid Surface as Part of Chemical Equilibrium Computations," Technical Report EQ 73-01, 1973, California Institute of Technology, Pasadena, Calif.

52. McDuff, R. E. and Morel, R. M. M., "Description and Use of the Chemical Equilibrium Program REDEQL2," Technical Report EQ-73-02, 1973, California Institute of Technology, Pasadena, Calif.

53. Denbigh, K., The Principles of Chemical Equilibrium, with Applications in Chemistry and Chemical Engineering, Cambridge University Press, Cambridge, Mass., 1966.

54. Kramer, J. R., "Equilibrium Models and Composition of the Great Lakes," Equilibrium Concepts in Natural Water Systems, Advances in Chemistry Series, American Chemical Society, Washington, D. C., Vol 67, 1967, pp 243-354.

55. Morel, F. and Morgan, J. J., "A Numerical Method for Computing Equilibria in Aqueous Chemical Systems," Environmental Science and Technology, Vol 6, No. 1, 1972, pp 58-67.

56. Stumm, W. and Morgan, J. J., Aquatic Chemistry, An Introduction Emphasizing Chemical Equilibria in Natural Waters, Wiley-Interscience, New York, 1970, p 233.

57. Kramer, J. R. et al., "Lake Erie Time Study," Paper No. 4, 1970, Canada Centre for Inland Waters, Burlington, Ontario.

58. Bird, R. B., Stewart, W. E., and Lightfoot, E. N., Transport Phenomena, Wiley, New York, 1966.

59. Patten, B. C., "Mathematical Models of Plankton Production," International Revue der Gesamten Hydrobiologie, Vol 53, No. 3, 1968, pp 357-408.

60. Riley, G. A., "Factors Controlling Phytoplankton Populations on Georges Bank," Journal, Marine Research, Vol 6, No. 1, 1946, pp 54-73.

61. Riley, G. A., Stommel, H., and Bumpus, D. F., "Quantitative Ecology of the Plankton of the Western North Atlantic," Bulletin, Bingham Oceanographic College, Vol 12, No. 3, 1949, pp 1-169.

62. Steele, J. H., "Plant Production in the Northern Sea," Rapp. Cons. Explor. Mer., Vol 144, 1958, pp 79-84.

63. Davidson, R. S. and Clymer, A. B., "The Desirability and Application of Simulating Ecosystems," New York Academy of Science, Vol 128, 1966, pp 790-794.

64. Chen, C. W. and Orlob, G. T., "Final Report, Ecological Simulation for Aquatic Environments," Dec 1972, Water Resources Engineers, Inc., Walnut Creek, Calif.

65. Hydroscience, Inc., "Limnological Systems Analysis of the Great Lakes, Phase I - Preliminary Model Design," Mar 1973, Westwood, N. J.

66. Baca, R. G. et al., "A Generalized Water Quality Model for Eutrophic Lakes and Reservoirs," Aug 1974, Battelle Pacific Northwest Laboratories, Richland, Wash.

67. Lombardo, P. S., "Critical Review of Currently Available Water Quality Models," Jul 1973, Hydrocomp, Inc., Palo Alto, Calif.

68. Di Torro, D. M., O'Connor, D. J., and Thomann, R. V., "A Dynamic Model of the Phytoplankton Populations in the Sacramento-San Joaquin Delta," Nonequilibrium Systems in Natural Water Chemistry, Advances in Chemistry Series, American Chemical Society, Washington, D. C., Vol 106, 1971, pp 131-180.

69. Bella, D. A., "Simulating the Effect of Sinking and Vertical Mixing on Algal Population Dynamics," Journal, Water Pollution Control Federation, Vol 42, No. 5, Part 2, May 1970, pp 140-152.

70. Male, L. M., "A Temporal-Spatial Model for Studying Nutrient Cycling Dynamics of a Phytoplankton Production System. Part I - Development of Model," Quantitative Science Paper No. 35, 1973, Center for Quantitative Science in Forestry, Fisheries, and Wildlife, University of Washington, Seattle, Wash.

71. Parker, R. A., "Capabilities and Limitations of a Nutrient-Plankton Model," Modeling the Eutrophication Process, Proceedings, Workshop held at Utah State University, Logan, Utah, Nov 1973, pp 121-130.

72. Dugdale, R. C., "Nutrient Limitation in the Sea: Dynamics, Identification, and Significance," Limnology and Oceanography, Vol 12, 1967, pp 685-695.

73. Koonce, J. F. and Hasler, A. D., "Phytoplankton Succession and a Dynamic Model of Algal Growth and Nutrient Uptake," Eastern Deciduous Forest Biome Memo Report No. 72-114, 1972, Madison, Wis.

74. Bierman, V. J. et al., "Multi-Nutrient Dynamic Models of Algal Growth and Species Competition in Eutrophic Lakes," Modeling the Eutrophication Process, Proceedings, Workshop held at Utah State University, Logan, Utah, Nov 1973, pp 89-109.

75. Lassiter, R. R. and Kearns, D. K., "Phytoplankton Population Changes and Nutrient Fluctuations in a Simple Aquatic Ecosystem Model," Modeling the Eutrophication Process, Proceedings, Workshop held at Utah State University, Logan, Utah, Nov 1973, pp 131-138.

76. Cordeiro, C. F., Echelberger, W. F., Jr., and Verhoff, F. H., "Rates of Carbon, Oxygen, Nitrogen, and Phosphorus Cycling Through Microbial Populations in Stratified Lakes," Modeling the Eutrophication Process, Proceedings, Workshop held at Utah State University, Logan, Utah, Nov 1973, pp 111-120.

77. Larsen, D. P., Mercier, H. T., and Mabreg, K. W., "Modeling Algal Growth Dynamics in Shagawa Lake, Minnesota, with Comments Concerning Projected Restoration of the Lake," Modeling the Eutrophication Process, Proceedings, Workshop held at Utah State University, Logan, Utah, Nov 1973, pp 15-31.

78. Sibert, J. and Parker, R. R., "A Numerical Model to Demonstrate the Effect of Pulpmill Effluent on Oxygen Levels in a Stratified Estuary," Technical Report No. 307, 1972, Fisheries Research Board of Canada, Pacific Biological Station, Nanaimo, B. C.

79. Bloom, S. G., Levin, A. A., and Raines, G. E., "Mathematical Simulation of Ecosystems - A Preliminary Model Applied to a Lotic Freshwater Environment," Research Report, Apr 1969, Battelle Memorial Institute, Columbus, Ohio.

80. Eggloff, D. A. et al., "Total Ecosystem Model for a Cove in Lake Texoma," Contributions in Systems Ecology, No. 00, University of Georgia, Athens, Ga.

81. Bloomfield, J. A., "Aquatic Modeling in the Eastern Deciduous Forest Biome, U. S. - International Biological Program," Modeling the Eutrophication Process, Proceedings, Workshop held at Utah State University, Logan, Utah, Nov 1973, pp 139-158.

82. Huff, D. D. et al., "Simulation of Urban Runoff, Nutrient Loading, and Biotic Response of a Shallow Eutrophic Lake," Modeling the Eutrophication Process, Proceedings, Workshop held at Utah State University, Logan, Utah, Nov 1973, pp 33-35.

83. Titus, J. E. et al., "Production Model for Myriophyllum spicatum L.," Eastern Deciduous Forest Biome Memo Report No. 72-108, 1972, Madison, Wis.

84. Kitchell, J. R. et al., "Implementation of a Predator-Prey Biomass Model for Fishes," Eastern Deciduous Forest Biome Memo Report No. 72-118, 1972, Madison, Wis.

85. Lighthart, B., "A Simple Aquatic Carbon Cycle Model," Internal Report No. 83, 1972 Annual Report, Coniferous Forest Biome, Seattle, Wash.

86. Dettman, E. H., "A Model of Seasonal Changes in Total Nitrogen Concentration in the Lake Wingra Water Column," EDFB-IBP-72-12, 1972, Oak Ridge National Laboratory, Oak Ridge, Tenn.

87. Hydrologic Engineering Center, "Water Quality for Reservoir-Riverine Systems," Draft Report, Jul 1974, Davis, Calif.

88. Boling, R. H., Jr., et al., "Ecosystem Modeling for Small Woodland Streams," Michigan State University, East Lansing, Mich.

89. __________, "Toward a Dynamic Model of Detritus Processing in Stream Ecosystems," Ecology, Vol 56, No. 1, 1975, pp 141-151.

90. McIntire, D. C., "Periphyton Dynamics in Laboratory Streams: A Simulation Model and Its Implications," Ecological Monographs, Vol 43, No. 3, 1973, pp 399-420.

91. Pomeroy, L. R. et al., "Nutrient Flux in Estuaries," Nutrients and Eutrophication, Special Symposia, American Society of Limnology and Oceanography, Vol I, 1972, pp 274-291.

92. Walsh, J. J. and Dugdale, R. C., "Nutrient Submodels and Simulation Models of Phytoplankton Production in the Sea," Nutrients in Natural Waters, Wiley-Interscience, New York, 1972, pp 171-191.

93. MacAuthur, R. H. and Wilson, E. O., The Theory of Island Biogeography, Princeton University Press, Princeton, N. J., 1967.

94. Keeley, J. W. and Engler, R. M., "Discussion of Regulatory Criteria for Ocean Disposal of Dredged Materials: Elutriate Test Rationale and Implementation Guidelines," Miscellaneous Paper D-74-14,

Mar 1974, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

95. Lee, G. F. and Plumb, R. H., "Literature Review on Research Study for the Development of Dredged Material Disposal Criteria," Contract Report D-74-1, Jun 1974, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.; prepared by Institute for Environmental Studies, University of Texas, under Contract No. DACW-39-74-C-0024.

96. Gannon, J. E. and Beeton, A. M., "Studies on the Effects of Dredged Material from Selected Great Lake Harbors on Plankton and Benthos," Special Report No. 8, p 82, 1969, Center for Great Lakes, University of Wisconsin, Milwaukee, Wis.

97. Flemer, D. A. et al., "Biological Effects of Spoil Disposal in Chesapeake Bay," Journal, Sanitary Engineering Division, American Society of Civil Engineers, Vol 94, No. SA4, Aug 1968, pp 683-706.

98. Gannon, J. E. and Beeton, A. M., "Procedures for Determining the Effects of Dredged Sediments on Biota-Benthos Viability and Sediment Selectivity Tests," Journal, Water Pollution Control Federation, Vol 43, 1971, pp 392-398.

Table 1

Ecological Problems Related to Dredged Material Disposal and Applicable Modeling Approaches

Ecological Problem Areas	Applicable Modeling Approaches						
	Physical			Mathematical			
	B	M	SE	DO	CHEM	PHYTO	ECO
Land and confined disposal							
Colonization and ecological succession	--	*	--	--	--	--	**
Biological productivity	--	*	*	--	--	--	--
Species diversity	--	--	--	--	--	--	--
Material cycling†	--	*	*	--	--	--	**
Return flows and receiving water impacts	--	*	*	*	--	**	**
Habitat creation							
Colonization and ecological succession	--	*	--	--	--	--	**
Biological productivity	--	*	*	--	--	--	**
Species diversity	--	--	--	--	--	--	--
Material cycling†	--	*	*	--	--	--	**
Artificial establishment techniques	--	*	*	--	--	--	--
Open-water disposal							
Pelagic							
Oxygen budget analysis	--	--	--	*	--	--	**
Biological productivity	--	*	*	--	--	**	**
Species diversity	--	--	--	--	--	--	--
Material cycling†	--	*	*	--	--	--	**
Benthic							
Direct smothering of benthic organisms	--	*	--	--	--	--	--
Colonization and ecological succession	--	*	--	--	--	--	**
Biological productivity	--	*	*	--	--	--	**
Species diversity	--	--	--	--	--	--	--
Material cycling†	--	*	*	--	--	--	**
Pollution criteria development	*	*	--	*	**	**	**

Notes: B = bioassays, M = microcosms, SE = scaled ecosystem, DO = dissolved oxygen, CHEM = chemical, PHYTO = phytoplankton, ECO = ecosystem.

* State of the art ready for application with only minor adaptations.

** State of the art not ready for application but development for selected purposes is feasible.

† Includes contaminant mobilization and transport.

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Hall, Ross W
Application of ecosystem modeling methodologies to dredged material research, by Ross W. Hall, Howard E. Westerdahl, [and] Rex L. Eley. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1976.
65 p. illus. 27 cm. (U. S. Waterways Experiment Station. Technical report D-76-3)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under DMRP Work Unit 1D04.
References: p. 58-65.

1. Dredged material. 2. Dredged material disposal. 3. Ecosystems. 4. Mathematical models. 5. Physical models. I. Eley, Rex L., joint author. II. Westerdahl, Howard E., joint author. III. U. S. Army. Corps of Engineers. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Technical report D-76-3)
TA7.W34 no.D-76-3